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6166-01, Session 1

Conceptual design and multidisciplinary optimization of in-plane morphing wing structures

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Conventional air vehicles are designed and optimized for specific flight conditions/profiles. When the vehicle maneuvers away from these design points, the performance often declines dramatically. Although the ability to adapt air vehicle shape to attain an optimum flight performance is highly desirable, the conventional fixed wing design is technically limited to accomplish this revolutionary performance objective. Therefore, major research efforts have been spurred recently to develop concepts, methodologies, and ideas to efficiently morph air vehicle geometry into optimum shapes depending on flight environments.

The main focus of this research is to investigate the development of a multidisciplinary design optimization methodology to determine the structural configuration that enables large scale area changes. The optimum structural configuration translates to simultaneous determination of optimum actuator placement, hinge/joint placement, and structural topology. The objective function will involve total actuator energy and shape-matching error terms. Although many argue that wing shape and its structural configuration should be a resultant of performance objective, the shape-matching objective is suitable for the present work due to its characteristics of disfavoring out-of-plane structural deformation. Additionally, total actuator energy minimization provides for an efficient distribution of an actuation system design as well as determination of actuator size requirement for a particular morphing wing design. Finite element analysis will be performed within each iteration of optimization process to evaluate objective function and static equilibrium constraints. In order to solve this multidisciplinary optimization problem, gradient-based optimization methods, such as Globally Convergent Method of Moving Asymptote.

For this paper, the wing design will focus on an in-plane morphing geometry. The in-plane morphing wing model is based on the concept similar to variable geometry truss and rigid-body spring model. The analysis model is developed to meet several important criteria: It must allow large rigid-body displacement, as well as variation in planform area, with minimum strain on structural members while retaining acceptable numerical stability for finite element analysis. Preliminary work has indicated that addressed modeling concept meets the criteria and is suitable for the purpose. Optimization will be performed on the ground structure based on this modeling concept with design variables that control the system configuration. In other words, states of each element are design variables and they are to be determined through optimization process. In effect, the optimization method assigns morphing members as 'soft' elements, non-morphing members as 'stiff' elements, and non-existent members as 'voids'. In addition, the optimization process determines the location and force intensities of distributed actuators, which is represented computationally as equal and opposite nodal forces with soft axial stiffness.

Preliminary investigations successfully demonstrated that addressed design/optimization scheme can provide a proper placement of joints and actuators, as well as magnitude of actuator forces. With further study and refinement, we believe that constructive solution to the addressed multidisciplinary problem can be obtained. It is expected that the research will be an important "first-step" to the topology synthesis of distributed actuation system solution for morphing air vehicle design of the future.

6166-02, Session 1

A methodology for optimal structural design of a morphing aircraft wing using non-dominated sorting genetic algorithm II

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Achieving multi-mission capability with a single aircraft through in-flight morphing of the wing is highly beneficial due to efficiency under different flight conditions such as cruise and dash. In addition higher maneuverability is possible from using such a vehicle. As opposed to traditional wing morphing where discrete surfaces such as hinged flaps and ailerons are used, current research focus is directed towards achieving continuous morphing in order to reduce drag from geometric discontinuities.

The present research aims to achieve continuous wing morphing by employing a wing structure comprising of an optimized internal layout of cables and struts. Cables are used as actuators while struts provide rigidity to the wing. In addition to achieving continuous morphing by changing cable length, this structure has the advantage of being light in weight.

In our previous work, a discrete Genetic Algorithm has been used to obtain an optimal layout of cables and struts in the wing body. Large deformation using non-linear Finite Element Analysis was employed to calculate the nodal deflections. Although the algorithm was successful in generating optimal topologies, the amount of actuation in cables could not be optimized due to the discrete nature of the design variables. This limitation has been removed in the current work.

The current work discusses a methodology for optimal structural design of the continuously morphing tendon actuated wing using Non-dominated Sorting Genetic Algorithm (NSGA II). The NSGA II is an elitist strategy which can be used to solve a multi-objective, multi-constrained problem with mixed (discrete-continuous) design variables. Non-linear Finite Element Analysis (FEA) is used in the function evaluation to account for large displacement requirements of the application. Serial and parellel versions of the algorithm are employed in order to speed up the computationally expensive function evaluation. The algorithm is used for obtaining optimal cable and strut layout for two example designs; the NASA's Hyper-Elliptic Cambered Section (HECS) wing and the NextGen Aeronautics' TSCh wing. The algorithm implementation, computation issues and results are presented.

6166-03, Session 1

Optimal actuation location within a morphing wing scissor mechanism configuration

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New design solutions using structural mechanization concepts with distributed actuation concepts have the potential to revolutionize air vehicle over a wide range of applications from micro air vehicles weighting less than a pound to larger unmanned systems weighting 10,000s of lbs. There is currently a large focus on radically changing planform parameters of a wing to enable it to perform over at a variety of design points of interest. One of the proposed morphing concepts is based on in-plane motion of the wing. It uses multiple cells of scissor mechanism to change wing area and sweep angle with distributed actuation system. One of the concerns of enabling this wing design is to find an optimal location of actuator within a unit scissor mechanism that can satisfy shape change requirements with minimum actuation energy to reduce the size of the entire actuation system. In this paper, the optimal location of actuator within an unit cell for further exploration of the distribution of actuators and the verification of numeric result using test result will be followed.

We start modeling a single cell representation of the scissor mechanism. This cell contains four linkages connected by pin joints, a single actuator, a two springs to represent a flexible skin in both in-plane directions, and an external load. Equilibrium equations are developed using statics and virtual work equations. The objective function is to maximize the efficiency of an unit cell model that is defined as useful work over input work with two constraints; one is to reduce the transferred force from the external force to the actuator less than the maximum actuator force. Otherwise the cell will not move to the desired direction because actuator force is unable to overcome external load. The other is to require the ratio of output displacement over input displacement, i.e., geometrical advantage (GA), of the cell to be larger than a prescribed value. A known solution of the most energy efficient location of the actuator is to put each ends of an actuator on two hinges facing each other. However, the actuator usually located on linkages next to each other to maximize displacement using leveraging effect due to the limitation of the actuator stroke. Sequential quadratic programming is used to solve the optimization problem.

This process suggests a systematic approach to identify an optimum location of an actuator and to avoid the selection of location by trial and error. Preliminary results show that optimum locations of an actuator can be selected out of feasible regions according to the requirements of the problem such as a higher GA, a higher efficiency, or a smaller transferred force from external force. Results in the final paper will include analysis of multiple cell wing structure.

6166-04, Session 1

Active vibration control with optimized piezoelectric topologies

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Vibration control using piezoelectric materials and the optimal use of these materials has been the focus of many research endeavors in active control systems. Commonly, optimization research has focused on the location and/or the number of actuators; in general, they used expense global optimization routines. However, studies on piezoelectric topology optimization using homogenization models have been used to determine optimal microstructure, optimal topology of a piezoelectric sensor , and optimal topology of a piezoelectric actuator on a static beam. Little work has been done to determine the optimal topology of a piezoelectric actuator under harmonic loading to maximize the vibration effectiveness.

Interest in topology optimization has grown considerably with the advent of computing power. Bendsoe and Kikuchi first introduced the homogenization method for determining the optimal topology of a structural problem. Work was done by Silva and Kikuchi which demonstrated topology optimization of piezoelectric materials. Drenckhan and Lumsdaine3 investigated optimal topologies of a piezoelectric actuator mounted on a cantilever beam under a concentrated static load at the free end. Parsons et al extended this work to a harmonic load applied at the free end; that work, however, was only a preliminary study on active layer damping using piezoelectrics. This research will extend Parsons' work and fully explore piezoelectric parameters and optimal piezoelectric actuator topologies.

This study focuses on the optimal topology of a piezoelectric actuator bonded to a cantilever beam under steady-state harmonic load. The piezoelectric material applied to the bottom of an aluminum base beam acts as the sensor, and the piezo on the top is the actuator. The piezoelectric material is optimized using a continuous "artificial material" model optimized with a sequencial linear programming (SLP) algorithm.

The finite element model is employed using the commercial finite element package ABAQUS and is broken into layers: one layer for the piezoelectric sensor, one layer for the elastic beam, and multiple layers (1 to 5) for the piezoelectric actuator. All layers contain the same number of four-node continuum elements along the length. The finite element discretization may be a substantial source of error. To help minimize this error, the elements aspect ratio is kept below one. Additionally, a convergence study shows a reasonable optimization result for the finite element model.

The active vibration control is achieved using distributed control theory. First, ABAQUS passes the stiffness and mass matrices for non-active control model to Matlab. Matlab builds the global mass and stiffness matrix (which includes the beam, actuator, and sensor) and applies a control law to the actuator based on the sensor's degrees-of-freedom. The displacement of the free end is then determined from the system of equations constructed from the global mass and stiffness matrices. The model is verified with an analytical formulation.

Before optimization, a parameter study is performed to examine various piezoelectric characteristics. Assorted piezoelectric (piezo-ceramics) materials are explored to determine the most effective one. Additionally, the angle of polarization of the piezoelectric actuator is investigated. Normally, the 3-1 orientation is used in this type of sensor and actuator setup. However, this work further examines the effects of changing the poling angle. Finally, the parameter study includes a look at the gain applied to the actuator. Too much gain can "over correct" the beam causing problems with the optimization routine. With the parameters set, the optimal actuator and sensor design is analyzed.

The actuator and sensor design is determined using topology optimization. Several techniques are available for manipulating the topology. One possibility is that the elements could be modeled using a binary discrete variable optimization where each element would be either void or contain 100% piezoelectric material. Since this technique would require a global optimization algorithm, this routine would have an exorbitant computational cost. The alternative approach, and the method selected for this work, is to use a local optimization algorithm that allows the material properties to vary for each element. Each element can have between 0 to 100% material and, thus, the design variables are continuous.

A sequential linear programming (SLP) algorithm is used to solve the optimization problem. SLP linearizes around the current design point in each iteration, and the next point is computed using linear programming until the convergence criterion is met. SLP is a robust code that is capable of handling large numbers of local minima. The commercial code VisualDOC is used to implement the SLP algorithm. As with all local optimization routines, the result may be a local minimum and not the global minimum. To help ensure the result, a sequential quadratic programming (SQP) algorithm is used to verify the convergence. However, SQP is still a local optimization method. Even though SQP may still converage on a local minimum, the new topology out performs the initial configuration.

The overall topology optimization scheme for the actuator and sensor occurs in two main steps. First, ABAQUS is used to determine the mass and stiffness matrices for the non-actively controlled dynamic model, and Matlab reads in these mass and stiffness matrices. Additionally, Matlab manipulates these matrices to include active control of the structure. Secondly, VisualDOC determines the optimal topology of the actuator elements given an initial configuration where all the material is distributed evenly along the length of the beam. The objective function for VisualDOC is evaluated with Matlab, and the gradient is calculated using finite differencing. Using the mass and stiffness matrices in Matlab saves computational time since ABAQUS has to only run once. However, the unfortunate side effect of numerically evaluating the gradient and objective function is the potential for significant errors and/or large costs in computational time. To help alleviate this problem, VisualDOC reads in the analytic gradients calculations from Matlab. However, this does not completely eliminate the numerical errors that may be in the finite element model and optimization calculations.

The optimization results show that a substantial decrease in displacement of the free end for the first mode can be achieved by changing the actuator topology; Figure 2 shows the results for a one layer topology optimization with an initial piezoelectric actuator of 20% material fraction.

Additionally, optimizing the sensor topology and polarization direction, determining a desirable gain, and selecting the most effective piezoelectric material can greatly suppress the vibrations of the cantilevered beam.

6166-05, Session 1

Analytical modeling and piezoelectric actuator configuration optimization for an adaptive composite satellite dish

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Adaptive composite panels have great potentials to be used as common structures in various industrial fields and main components of future spacecrafts. Specially, particular adaptive composite material applications such as a composite antenna or a composite satellite dish are gaining researchers' attentions. As a result, the knowledge of their modal behavior has to be explored in order to establish a technological roadmap for their applications. As a basic stepping stone, numerous models have been developed recently to describe the dynamics of adaptive composite panels with surface-mounted piezoelectric (PZT) patches using various methods. Although, much research has been performed on the dynamics of beams, rectangular plates, even circular plates, less research has been performed on shallow shell such as a composite satellite dish.

In this paper, the dynamic analysis of a satellite dish with respect to spherical polar coordinate system is investigated. In this complicated three-dimensional case, the method of separation of variables is employed to obtain the explicit solution of the partial differential governing equation of the composite satellite dish. Then, the mode shape functions are expanded in combination of periodic functions, associated Legendre functions, and spherical Bessel functions. The validation of the theoretical model is performed by comparing the developed analytical mode shapes with finite element analysis mode shapes.

Also, employing the developed model, the norm-2 of LQR optimal feedback gain vector is set as the objective function of the optimization strategy to obtain the optimal actuator location coupled with the control law, with which good structural vibration suppression as well as less control energy consumption can be achieved by the linear quadric regulator (LQR).

6166-06, Session 2

A study of optimal locations of piezo-patch actuators and sensors on a cantilever beam for maximum frequency gaps

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Active vibration control is implemented using multiple piezoelectric actuators and sensors bonded to the top and bottom surfaces of a cantilever beam. The control is exercised using closed-loop displacement feedback. The objective of the study is to determine the optimal locations of patch actuators and sensors such that the fundamental frequency or the frequency gap between higher frequencies of the beam is maximized. Maximizing the fundamental frequency is useful in those cases where the excitation frequency is specified to be less than the fundamental frequency to avoid resonance. However, in some cases the excitation frequency can be placed in between two higher order frequencies. This arrangement also avoids the resonance. In these cases the design requirement is to maximize the difference between the two higher order frequencies such as between the first and second frequencies or between the second and third frequencies, etc. In the present study the fundamental frequency and the frequency gaps between the higher order frequencies are investigated with respect to actuator and sensor locations with a view towards determining the optimal locations for largest frequency gaps.

The differential equation governing the vibrations of a feedback controlled cantilever beam/piezo patch system is solved using an integral equation approach. The equivalent integral equation formulation of the problem avoids the discontinuities

which arise due to partial length piezo patches. The solution is approximated using the eigenfunctions of the host structure which lead to a system of algebraic equations in the final step of the solution procedure. The numerical results are given for various patch combinations and the optimal locations of the actuators and the sensors are determined. It is observed that the optimal locations of the piezo patches depend on the specific frequency gap as well as the patch configurations.

6166-08, Session 2

Design of functionally graded piezoelectric actuators using topology optimization

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Functionally Graded Materials (FGMs) possess continuously graded material properties and are characterized by spatially varying microstructures. The smooth variation of properties may offer advantages such as reduction of stress concentration and increased bonding strength. Recently, this concept has been explored in piezoelectric materials to improve properties and to increase the lifetime of bimorph piezoelectric actuators. Usually, elastic, piezoelectric, and dielectric properties are graded along the thickness of a piezoceramic FGM. Thus the gradation law of piezoceramic properties can influence the performance of piezoactuators. In this work, topology optimization has been applied to find the optimum gradation variation in piezoceramics FGMs in order to improve actuator performance measured in terms of output displacements. A bimorph type actuator design is considered. Accordingly, the optimization problem is posed as finding the optimized gradation variation of piezoelectric properties that maximizes output displacement or output force in the tip of bimorph actuator. The optimization algorithm combines the finite element method with sequential linear programming (SLP). The finite element method applied is based on the graded finite element concept where the properties change smoothly inside the element. This approach provides a continuum approximation of material distribution (CAMD), which is appropriate to model FGMs. The alternative FGM modelling using traditional FEM formulation and discretizing the FGM into layers gives a discontinuous stress distribution, which is not compatible with FGM behavior. The present results consider gradation between two different piezoceramic properties and consider two-dimensional models with plane strain assumption.

The practical use of the approach proposed here can dramatically broaden the range of application of functionally graded piezoelectric actuators in the field of smart structures.

6166-09, Session 2

Optimum place of piezoelectric material in the piezoactuator design

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Piezoelectric mechanisms offer significant promise in a wide range of applications such as cell manipulation, microsurgery, nanotechnology processes, and many other fields. The piezoelectric mechanisms considered in this work essentially consist of a flexible structure actuated by piezoceramics that must generate output displacement and force at a certain specified point of the domain and direction. The flexible structure acts as a mechanical transformer by amplifying and changing the direction of piezoceramics output displacements. Thus, the development of piezoelectric actuators requires the design of actuated compliant mechanisms that can perform complex movements. The design of these piezoelectric mechanisms are complex and a systematic design method, such as topology optimization has been successfully applied in the latest years, with appropriate formulation of the optimization problem to obtain optimized designs. However, in these previous piezoelectric actuator design formulations, piezoceramics position are usually kept fixed in the design domain and only the flexible structure is designed by distributing only conventional material (aluminum, for example). This imposes a constraint in the position of piezoelectric material in the optimization problem limiting the optimality of the solution. Thus, in this work, a formulation that allows the simultaneous search for an optimal topology of a flexible structure as well as the optimal positions of the piezoceramics in the design domain, to achieve certain specified actuation movements, will be presented. This can be achieved by allowing the simultaneous distribution of conventional and piezoelectric material in the design domain. The optimization problem is posed as the design of a flexible structure together with optimum positions of piezoelectric material that maximizes output displacements or output forces in a certain specified direction and point of the domain. The method is implemented based on the SIMP material model where fictitious densities are interpolated in each finite element, providing a continuum material distribution in the domain. The optimization algorithm employed is based on sequential linear programming (SLP) and different types of piezoelectric mechanisms considering different kinds of output displacement were designed to demonstrate the usefulness of the proposed method. Although the presented examples are limited to two-dimensional models, this is appropriate since most of the applications for such piezoelectric mechanisms are planar devices. The use of topology optimization for the design of piezoelectric mechanisms is a novel approach that has the potential to dramatically broaden the applied range of such devices, especially in the field of smart structures.

6166-10, Session 2

Multi-actuated functionally graded piezoelectric micro-tools design using topology of optimization

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The micro-tools considered in this work essentially consist of a multi-flexible structures actuated by two or more piezoceramic devices that must generate different output displacements and forces at different specified points of the domain and on different directions. The multiflexible structure acts as a mechanical transformer by amplifying and changing the direction of the piezoceramics output displacements. Thus, the development of these piezoelectric micro-tools requires the design of actuated compliant mechanisms that can perform detailed specific movements.

Micro-tools offer significant promise in a wide range of applications such as cell manipulation, microsurgery, and micro/nanotechnology processes. Although the design of these micro-tools is complicated by the coupling between movements generated by various piezoceramics, it can be realized by means of the topology optimization method. Recently, the concept of functionally graded materials (FGMs) has been explored in piezoelectric materials to improve the properties and increase the lifetime of piezoelectric actuators. In an FGM piezoceramic, usually, elastic, piezoelectric, and dielectric properties are graded along the thickness. Thus, the objective of this work is to study the influence of the piezoceramic property gradation in the design of the multiflexible structures of piezoelectric micro-tools using topology optimization. The optimization problem is posed as the design of a flexible structure that maximizes different output

displacements or output forces in different specified directions and points of the domain, in response to different excited piezoceramic portions, while minimizing the effects of movement coupling. The method is implemented based on the solid isotropic material with penalization (SIMP) model where fictitious densities are interpolated in each finite element, providing a continuum material distribution in the domain. The optimization algorithm employed is based on sequential linear programming (SLP).

As examples, designs of an XY nano-positioner actuated by two FGM piezoceramics and a micro-gripper actuated by three FGM piezoceramics are considered. The obtained designs are compared with designs considering homogeneous piezoceramics. The present examples are limited to two-dimensional models because most of the applications for such micro-tools are planar devices.

6166-11, Session 3

Minimum mass design of tensegrity towers and plates

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In this paper we advance the state-of-the-art of Tensegrity systems by showing how to design towers and plates which are made of a number of stable units, called “Snelson Prisms”, so named to honor the artist that first constructed one as an art-form.

Tensegrity structures can be optimized to minimize mass and maximize strength due to the fact that tensile elements can carry more load per mass than compressive elements. By using more strings, tensegrity structure design can save mass. For instance, in the simplest possible three dimensional traditional frame structure, a tetrahedron, one needs six bars to keep four nodes in equilibrium. In the simplest three dimensional tensegrity structure, one can keep six nodes in equilibrium using only three bars.

The design of tensegrity towers and plates presented in this work is characterized by the sites of the connections with adjacent members, and the parameters of each Snelson Prism. These formulas are analytical in nature, allowing the user to substitute any material choice and any bounds on strength and stiffness.

Since the properties of tensegrity structures are scalable, we can also save mass by taking advantage of geometry. For instance, in previous works we have shown how to apply self-similar iterations, to replace an individual bar by yet another tensegrity structure with less mass, without sacrificing strength, leading to the concept of tensegrity fractals. In this paper we show that a similar result, that is, minimization of the total mass on a finite number of iterations can be achieved on more traditional geometries, such as towers (columns) and plates. By increasing

the number of units (Snelson Prisms) in tensegrity towers and plates it is possible to reduce mass without changing the external dimensions nor the strength of the resulting tensegrity system. These iterations allow the total mass of the structure to be minimized in a finite number of self-similar iterations.

6166-12, Session 3

Tensegrity structures in aquaculture installations

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Aquaculture is the fastest growing food production sector in the world and has experienced an increased annual production of close to ten percent in average since 1970. The future demand of seafood products could only be solved by developing offshore aquaculture due to an increasing number of installations and shortage of shelter locations. The quality of water is another reason for investigating offshore aquaculture. The extreme weather conditions experienced offshore leads to a focus on the development of new structure concepts, remote monitoring and a higher degree of automation.

This paper introduce the use of tensegrity structures in the design of aquaculture installations. The net spanning tensegrity structure will change its position and attitude as a function of environmental loading from waves and currents. A multi-objective control strategy is used on a controllable tensegrity structure to alter the structure geometry in an optimal manner as a trade-off between minimizing environmental loads and optimizing through-flow of water and net spanning volume.

A novel second order matrix differential equation form proposed by R. E. Skelton is used to describe the dynamics of this multi-body system. This form requires no matrix inversion and is therefore effective for analysis and control of systems with a large number of rigid bodies.

A simulation study with different hydrodynamic load conditions has revealed that new structure concepts and multi-objective control could reduce loading and increase fish welfare and efficiency of production.

6166-13, Session 3

A dynamic model for generating actuator specifications for small arms barrel active stabilization

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Over the past century, no significant modifications have been made to small arms; yet, it is still very difficult to attain higher marksmanship levels due to shooter induced disturbances. Modern advances in active stabilization based upon smart materials have the potential to reduce if not eliminate shooter induced disturbances increasing accuracy and thus mission effectiveness and survivability. Independent of the selected mode of actuation, piezoelectric or shape memory alloy, it is difficult to ascertain the actuator requirements due the unknown jitter introduced by a shooter's arm or shoulder physiological inputs. These specifications are necessary for the design of all elements of the active stabilization system including the actuator, controller and stabilizing mechanism (springs, dampers, levers, etc.).

This paper presents a generic analytical dynamic model of small arms that encapsulates all the key parameters necessary to predict the required actuation forces and displacements as functions of frequency. This model is unique because it captures the human interface - shoulder and arm - that introduces the jitter disturbance in addition to the geometry, inertial properties and active stabilization stiffness. Because no data to date is available for actual shooter-induced disturbance in field conditions, a method is given using the model to back solve from actual shooting range variability data the disturbance amplitude information relative to the input source (arm or shoulder). This modeling method is powerful because it can be applied to a wide range of hand-held weapons with varying kinematics, different frequency conditions and disturbances, and generates the actuator requirements (force, amplitude, frequency) for the active stabilization system in both the azimuth and elevation directions.

As validation, the model was applied to two very different weapon systems: M24 which is a sniper weapon with the active stabilization would operate between the stock and barrel and the disturbance is introduce via the stock, and the M16A4 where the active stabilization would operate between the shooter's forward hand and the barrel/stock assembly. In both cases, model based simulations provided significant insight into the interplay of the human - weapon - active stabilization interface. This included the effect of increasing frequency of shooter induced disturbances, the disturbance location (shoulder vs arm), the impact of active stabilization system stiffness, and required barrel rotation (or accuracy variability). An interesting finding is that the quasi-static solution always bounded the requirements for reasonable disturbance frequencies (less than 5 Hz), independent of the disturbance source, amplitude or stabilization stiffness, making it straightforward to set conservative specifications for the active stabilization actuator.

6166-15, Session 3

Low-order actuator influence functions for piezoelectric in-plane actuated tensioned circular deformable mirrors

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Lightweight, large deformable mirrors for space-borne optical telescopes and surveillance activities are an area of intense research to support astronomical exploration and national security objectives. Simply stated, space deployable, large-diameter, low areal density, optical quality surfaces are required to overcome limitations for all foreseeable launch vehicle packaging and payload constraints. The choice of a deformable mirror stiffened by membrane tension and forced by piezoelectric in-plane bimorph or unimorph actuators may be a desirable configuration. Compared to a conventional mirror where discrete actuators are attached to a rigid backing structure and operate directly against the mirror's non-reflecting face, the in-plane actuated mirror is lighter in weight, is capable of remote actuation, and is capable of higher spatial frequencies for a given number of actuators—all distinct advantages for space-borne operations. However, efforts to simply model the influence functions of deformable mirrors have long relied upon matching individual actuated shapes without regard to the domain of the mirror surface. Error terms, such as pinning errors, have dominated discussions utilizing these modeling efforts. Furthermore, the case of non-isotropic piezoelectric actuators is often ignored, although it is the most common type employed for in-plane actuation. A simplified model incorporating the domain of the mirror surface which allows for non-isotropic actuators is desired. The research presented herein is an incremental step towards quasi-static optical precision control of the envisioned large scale deformable mirror surface.

The analytic influence functions are determined using modeling techniques familiar in piezoelectric actuated structures where piezoelectric actuation is injected into the simplified governing partial differential equation via line moments. The method described herein prescribes an asymptotic solution to the partial differential equation, where scaling is achieved as the comparison in stiffness between flexural rigidity and tension. For an actuator pattern defined in radial coordinates, the first order solution solves the Poisson equation using Green's functions. The asymptotic solution is unique in that it highlights the effects of the tuning parameters such as membrane tension versus thickness which become tools at discretion of the design engineer.

The analytical approach in this presentation involves calculating the influence functions for this class of deformable mirror with a finite element model used as the truth source. Piezoelectric forcing is introduced to the finite element model through the familiar piezoelectric-thermal analogy, and the membrane is tensioned via a non-linear update to the stiffness matrix. The model, constructed in MSC.Nastran, is undergoing concurrent verification in a series of laboratory experiments.

Analytical results show the presented simplified solution closely replicates the non-linear finite element solution at a lower computational cost. Furthermore, by forming a model which incorporates the entire domain versus the use of localized influence functions, the negative effects of pinning errors are reduced. Moreover, the simplified influence function should prove useful to researchers seeking to implement control algorithms scaled to large-diameter space-borne systems, and for use in genetic, iterative algorithms for determination of actuation location, and for design/performance trade studies of membrane mirrors.

6166-16, Session 3

Experimental multi-input multi-output (MIMO) control of a smart fin

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Buffet induced tail vibration is a significant problem particularly for twin-tail fighter jets, which require frequent inspection to prevent catastrophic failure. In this paper an Aluminum fin was considered as a representative model of a typical fighter vertical tail with scaled dynamic modes and geometry. Piezoceramic actuators were bonded to both surfaces of the fin and accelerometers were used to monitor the dynamic response. The smart fin fabricated at the NRC laboratory. A modal analysis of the finite element model of the integrated smart fin provided the natural frequencies to compare with the experimental results. A Multi-Input Multi-Output (MIMO) control system was designed and implemented using the Simulink, the Real-Time Workshop, and the xPC TargetBox of Mathworks. Results demonstrated that the active control system reduced the vibration significantly and the MIMO control system demonstrated superior performance over the Single-Input Single-Output (SISO) controller for a broadband control of the smart fin.

The first two dynamic modes, i.e. first bending and first torsional modes, of the smart fin were considered in this study. Accelerometers were employed as sen-

sors and 24 Piezoceramic actuators were bonded to both sides of the fin. Some actuators were used as disturbance generators and others as control actuators. In order to excite/control the second mode, i.e. torsional mode, more effectively actuators were operated out of phase.

First, two independent SISO control systems for the first two dynamic modes of the smart fin were designed and implemented for narrow band control around each of these modal frequencies. Then, a MIMO control system was designed and implemented for broadband control.

The frequency response of the accelerometer to a random vibration without control and with the first mode SISO control was studied. The controller was effective for the first mode with peak vibration suppression of 78.5% but it was unable to suppress the second mode. However, the controller did not have any spillover effect to enhance the second mode. Also, the second mode SISO control system was able to suppress the second vibration mode induced by a random excitation effectively without causing spillover to the first mode. A reduction of 55.5% in the peak acceleration, is achieved for the second mode. Using the MIMO control system, both sets of excitation actuators were driven by a random signal to excite both modes effectively. The two sets of control actuators were then employed in the MIMO control loop to suppress the vibration over a broad range of frequency. The MIMO control system showed its superiority over the SISO controllers by suppressing the vibration over the broadband frequency. A simultaneous vibration reduction of 71.1% and 45.1% for the first and second vibration peaks respectively were achieved.

The active control systems were also tested with narrow band and broadband sine sweep excitations which demonstrated a robust and effective vibration control. Details of the control system and the complete experimental results will be presented in the full paper.

6166-17, Session 4

A reptation model for magnetic materials

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Reptation is a phenomenon affecting most ferroic materials. It may be observed by showing that several loops over the same input field (ferroelectric and ferromagnetic materials) or temperature (shape memory alloys) produce slightly varying polarizations/magnetizations/strains. This corresponds to varying displacements, which poses problems for actuators or sensors requiring high accuracy. While the underlying causes of reptation are complex and vary by material, the macroscopic behavior can be treated in a consistent manner which holds promise for real-time designs. A constituative reptation model is presented in the context of homogenized energy models, and its performance is analyzed. To simplify the discussion, magnetic materials are focused on, although the model itself has broader application.

6166-18, Session 4

An evolutive model for magnetostrictive interactions: existence of weak solutions

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The dynamics of magneto-elastic materials is described by a nonlinear parabolic hyperbolic system which couples the equations of the magnetization and the displacements. We propose a model for the two-dimensional case and establish the existence of weak solutions. Our starting point is the Gilbert-Landau-Lifschitz equation introduced for describing the dynamics of micromagnetic processes. Three terms of the total free energy are taken into account: the exchange energy, the elastic energy and the magneto-elastic energy usually adopted for cubic crystals. In this approach we neglect the contributions due to the anisotropy and the demagnetization effects. The analysis of the equations is carried out in 2D framework which allows us further simplificative hypotheses mainly concerning the assumption of small plane displacements. The paper is devoted to the existence of weak solutions for the proposed differential system. The existence theorem is proved combining the Faedo-Galerkin approximations with the penalty method which introduces a small parameter. The convergence as the parameter vanishes is deduced from compactness properties.

6166-19, Session 4

Modeling and characterization of a smart two-directions MOSFET magnetic sensor

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A great attention has been recently given to the characterization and realization of precise MOSFET magnetic field detectors. This is referred to the remarkable enhancement in device concepts and technology and because of the ever increased wide range of applications in which precise integrated circuit (IC) magnetic field detectors are required. However, most of the present used magnetic field detectors are either bulky, heavy, sophisticated, or can not be integrated using MOSFET technology in a single ship. On the other hand, theoretical models had been developed to determine the effect of magnetic fields on the electrical performance of active devices. However, some of these models has no coupling between the magnetic field and the electron transport equation. This limits the ability of these models to determine the effects of all device parameters and operating conditions of the detector sensitivity. On the other hand, sophisticated models which fully coupled Maxwell's equations with the device transport equations require high CPU time what limit the usage of these models as efficient CAD tools in the device structure optimization process.

The aim of the present work is to develop an accurate physical device simulator that can be efficiently used to characterize the operation and to optimize the structure of a new suggested smart two-directions MOSFET magnetic sensors. The limitation of the previous models and simulators are overcome by using an efficient coupling scheme of the external applied magnetic field in the device transport equations. The simulator is used to investigate the effect of different device and circuit parameters on the sensor sensitivity and hence to determine the best biasing conditions to have maximum sensitivity of the sensor.

The simulator is then applied to characterize the operation of a smart two-direction magnetic sensor. It is constructed of a square-looped source MOSFET surrounded by four lateral MOSFETs whose sources act as current collectors. Two of them are axially located along the x-direction and they are responsible of detecting the z-oriented magnetic fields while the other two are located along the z-direction and are responsible of detecting the x-field component.

The square-looped source structure provides a trapezoidal-formed channel, which enhances carrier heating even at small biasing voltages without need for scaling down the device geometry. In the absence of the magnetic field, the carrier substrate current penetrates into the bulk and the four lateral collectors accumulate equal currents, and a portion of this current (depending on the substrate bias) goes to the substrate terminal. In the presence of the magnetic field excursion caused by the presence of microwave signal, the symmetry of the substrate current flux is upset in such a manner that one or two collectors (depending on the orientation of magnetic field) accumulate more currents than the others.

The ability of the sensor to detect the direction of the applied magnetic field makes it possible to have two-direction sensor which is able to detect magnetic field variations in two perpendicular directions from d.c. to microwave ranges. The suggested sensor is found to have very high sensitivity, very good linearity, wide dynamic range of operation, and excellent resolution. Moreover the present detector overcomes the challenging problem of inability to determine the orientation of the magnetic field in conventional magnetic sensors.

6166-20, Session 5

Monte-Carlo simulation of ion transport at the polymer-electrode interface of high strain ionomeric

X. He, D. J. Leo, Virginia Polytechnic Institute and State Univ.

The transport of charge due to electric stimulus is the primary mechanism of actuation for a class of polymeric active materials known as ionomeric polymer transducers (IPT). Functionally an IPT is very similar to a piezoelectric transducer converting mechanical energy to electrical energy or vise-verse. It is believed that a larger polymer-electrode interface area increases the capacitance of IPT. Recent experimental results have demonstrated that increasing the volume percentage of conductive particles in the electrode increases the capacitance and performance of the transducers. The focus of this paper is to use a computational model to compare the difference before and after metal particle loading in the electrode. The model contains a 50nm 50nm 50nm lattice cells representing the IPT substrate. 1000 cations are distributed inside while the same number of negative charges are uniformly scattered and fixed as background charge. Before any metal particle loading, the system can be described purely by an ion hopping model with Monte Carlo simulation as thermally activated cations hop between multiwell energy structures by overcoming energy barrier with a hopping distance of 1nm each time. A step voltage is applied between the electrodes of the IPT. In one single simulation step, coulomb energy, external electric potential energy and intrinsic energy of the material are calculated and added up in energy wells around the cations. And then hopping rates in those potential hopping directions are obtained. Due to the random nature of the ion transitions, a weighting function from Monte-Carlo algorithm is added in to calculate the ion hopping time. Finally the minimum hopping time is chosen and one hopping event is accomplished. Both system time and ions distribution are updated before the next simulation loop. Periodical boundary conditions are applied when ions hop in the direction perpendicular to the electric field. The intrinsic energy term is adjusted to properly describe Nafion based IPT and help match the dynamic properties of IPT in the experiments. The influence of the electrodes on both faces of IPT is presented by

the method of image charges. The charge density at equilibrium state qualitatively matches the result from a continuum-based model. The property of charge density has charge neutrality over the most central of part of the membrane and the charge imbalance over narrow boundary layer close to the anode and cathode.

After metal loading in the electrode, at the place far from interface, ion hopping model with Monte-Carlo simulation still can be used to effectively describe ion transport inside the transducer. However, at the polymer-electrode interface, simulation will concentrate on varying the material properties near the electrode and analyzing the effect on ion transport. Results comparison includes the number of ions accumulated at the polymer-electrode interface and the time taken to reach the accumulation when the volume percentage of conductive particles in the electrode varies.

6166-21, Session 5

Dynamic modeling of the nonlinear response of ionic polymer actuators

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Ionic polymers are compliant, light weight materials that operate under low voltage levels as transducers. They can be used as both sensors and actuators for various applications, primarily those involving flexible structures. The electromechanical transduction properties of these materials were discovered just over a decade ago, spawning the development of ionic polymer research. While the debate continues over the dominant physical mechanisms of actuation, several model forms have been proposed. The majority of these existing models are stated to be linear approximations and some were derived with input-dependence. However, nonlinear characteristics have been observed in both the electrical and mechanical response of cantilever actuators, including harmonic distortion in the time-domain and magnitude scaling of the frequency response. Characterization results indicate that the nonlinear mechanisms are dynamic since they have dominance at low frequencies, but are essentially negligible as the excitation frequency increases. This research uses knowledge gained from the characterization results to develop a dynamic model that can predict the observed nonlinear behavior. The empirical model is constructed from input-output data collected using a Gaussian input current signal and is validated using the measured frequency response function and single-frequency sinusoidal responses. While this model does not derive any new physical laws, it does provide a phenomenological account for how nonlinearities affect the actuation response of ionic polymer transducers, which will be helpful for future modeling efforts and parameter studies. Additionally, with an identified model structure that can capture the nonlinear dynamics, ionic polymer actuators will be one step closer to system implementation.

6166-22, Session 5

Variational modeling of ionic polymer plate structures

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Ionomeric polymers are a promising class of intelligent material, which exhibit electromechanical coupling similar to that of piezoelectric bimorphs. Ionomeric polymers are much more compliant than piezoelectric ceramics or polymers and have been shown to produce actuation strain on the order of 2% at operating voltages between 1 V and 5 V. This performance indicates the potential for self-actuating devices manufactured from ionomeric polymers, such as deformable mirrors or low pressure pump diaphragms.

This paper presents a variational approach to the dynamic modeling of ionic polymer plates in rectangular coordinates. A linear matrix equation, which relates displacement and charge to applied forces and voltage, is developed then applied to shape control of a boundary-constrained plate. One of the more interesting aspects of the modeling method is the incorporation of empirically determined material properties, which have been shown to be highly frequency dependent. The matrices are calculated and solved for a discrete frequency vector resulting in frequency response functions or spatial solutions at an individual frequency.

An example model is developed and validated experimentally. Simulated frequency response functions are compared to experimental results for several spatial locations. Then spatial solutions are investigated at some frequencies identified by interesting characteristics of the frequency response functions. These spatial solutions are also compared to experimentally determined response shapes.

6166-23, Session 5

EAPap walking actuator device

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Initial Abstract of 8/9/05

Electroactive Paper has been proposed as a bio-inspired and friendly smart material and an Electroactive Polymer Actuator. One smart device that is within the present design capabilities of emerging EAPap materials is that of an ambulatory or walking actuator. Most prior EAPap materials have been too thin and flexible to allow them to carry sufficient weight for use in an ambulatory system. The move from 15 to 18 micron thickness EAPap materials to 30 micron and thicker papers with good electroactive action provides improved bending stiffness and tip forces so that walking devices are feasible.

We are constructing an elemental device constructed of two bending elements. Taken as a compound unit smart actuator, this device can perform forward or backward motion controlled by a simple signal generator with a staggered periodic signal to both elements. The performance of this unit varies with signal, so that as some specific frequencies and delays, it is able take advantage inertial effects to help it traverse a variety of terrains. This basic unit may be sufficiently robust to serve as one portion of a larger device capable of forward, backward, and side movement allowing it to follow a prescribed path or to take intelligent action in response to a specific mission requirement.

One of our concepts involves two bending elements interconnected at one location to promote repetitive walking motion.

6166-24, Session 6

Nonlinear vibration modes in microresonator arrays

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In the solid-state physics literature, nonlinear phenomena such as mode localization have been studied for a number of years. Energy can become localized at a specific location in a discrete system as a result of the nonlinearity of the system and not due to any defects or impurities within the considered systems. Intrinsic Localized Modes (ILMs), which are defined as localization due to strong intrinsic nonlinearity within an array of perfectly periodically oscillators, are of interest to the present work. Here, such localization is studied in the context of micro-cantilever arrays and micro-resonator arrays, and it is explored if an intrinsic localized mode can be realized as a nonlinear normal mode. The method of multiple scales is used as a part of the analysis to study the nonlinear vibration modes of the resonator arrays. Preliminary investigations to be reported in this article suggest that this is possible, and these results are believed to be important for future designs of micro-resonator arrays intended for signal processing, communication, and sensor applications.

6166-25, Session 6

Frequency-dependent modeling of nonlinear history effects in piezoceramic stack actuators

A. J. Kurdila, Univ. of Florida

No abstract available

6166-27, Session 6

Thermal-electrical-mechanical coupled FE buckling analysis of smart plates using discrete layer kinematics

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Piezoelectric materials and especially PZTs have been introduced in several scientific areas over the last decades. In combination with advances in control methods, areas of structural mechanics that were not implemented in real applications in the past, are now in the front line of development. Aeronautical structures take advantage from these developments as non-linear mechanics enters the stage which permits to expand the operational envelope of piezoelectric actuators by increasing their displacement and blocking force.

The issue of non-linear structures that amplify the actuation provided from piezoelectric elements has been shown for aeronautical applications in [1]; in this work, the potential of non-linear mechanics for increasing the performance of piezoelectric elements is clearly shown. Snap-through buckling is a step further in the direction of using non-linear mechanics for actuator design. Numerous buckling and postbuckling analysis publications have been presented treating the issue on a theoretical level, taking into account different parameters such as thermal forces [2], and in more complicated analyses both thermal and electrical forces [3]. Some researchers have also treated the subject using similar formulations implementing finite element solvers [4]; in most of the cases, the coupling exists between the mechanical and electrical field and an equivalent single layer theory is used (CLPT, FSDT, HSDT).

In the present work, a fully coupled thermal-electrical-mechanical constitutive formulation has been implemented in combination with a plate finite element and

discrete layer kinematics in order to asses the buckling behavior of smart plates of different thickness to length ratios. Non-linear terms due to large displacements are introduced. Additionally, the issue of buckling compensation through electrical actuation of the piezoelectric elements is examined. The thermal buckling is also examined introducing thermal effects (temperature gradients and heat flux). The coupling capabilities of the FE solver permit the prediction of the buckling onset in a more accurate way compared with a solver where the coupling capability between all fields does not exist and where thermal effects are represented through equivalent thermal forces. This is due to the fact that in the case of the fully coupled solver, the temperature distribution inside the structure is calculated through the heat transfer equations and thus the global temperature response is more accurately represented. This parameter is becoming more important as the plate thickness increases.

An important aspect is the examination of buckling onset due to the excitation of piezoelectric elements, in a precompressed beam. A high displacement actuator can be build using this phenomenon, since a slight excitation from piezoelectric elements can occur in buckling where displacements are orders of magnitude higher than the displacement of the piezoelectric element itself.

The discrete layer kinematics implemented in [5] for all degrees of freedom permit the accurate calculation of the global response of the structure, as well as the stress levels in each of its layers, as it has already been shown in [6]. Electrical and thermal degrees of freedom are also approximated through discrete layer kinematic assumptions. Compared with an equivalent single layer theory, the prediction is more accurate for all degrees of freedom especially for thick plates. Results from experimental procedures already performed are used to support the present analysis.

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6166-28, Session 6

Model validation of piezoelectric polymer applied to mm size microrobot I-SWARM

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In classical microrobotics, highly integrated and specialised robots have been developed in the past years, which are able to perform micromanipulations controlled by a central high-level control system. On the other hand, technology is still far away from the first "artificial ant" which would integrate all capabilities of these simple, yet highly efficient swarm building insects. The aim of the Integrated Project I-SWARM (FP6-2003-IST-507006) is the realisation of a "real" microrobot swarm, i.e. a thousand micro manufactured autonomous robots will be designed for the collective execution of different tasks in the small world. The function of the robots agents will be reduced to locomotion, integrated tool permitting basic manipulation, possibility to attach and release other agents, a limited capability to store information on the state of the agent as well as the possibility to transfer basic information between agent to agent.

In several insects the mechanical structure for locomotion is based on shells and muscles. Agile limbs can be made when a suitable muscle "actuator" is integrated with the shell structure. To mimic the biological world the materials for the backbone of the insect robot should be polymeric. A full custom IC will be designed and implemented for on-board power management and intelligence. The whole robot insect dimension is restricted to 1mm*2mm*2mm. As a locomotion principle 4 PVDF (Poly Vinylidene Fluoride) thin film multilayer pair legs should be implemented, each of them with a maximum surface of about 0.3mm*0.5mm.

In this paper an electro-mechanical model to describe the behaviour of a multiplayer PVDF smart structure as the proposed robot legs is presented. The study is based on the modal analysis of the partial differential equations governing the motion of an Euler-Bernouilly cantilever beam. A pair of linearly coupled piezoelectric equations between the mechanical and the electrical domains is used. An important element in the modelization of such materials is the energy losses term, in this paper a viscous damping contribution is considered which allows us to extract a more realistic constituent equations for the material to work as senor and actuator. The development of this equation as an infinite linear combination of each mode allows us to extract a compact lumped equivalent electrical circuit to work at any frequency region as sensor or actuator instead of the classical reduced models.

Once the theory is presented experimental measurements are developed for the model validation. The experiments are measured on custom made multilayer cantilever structures based on PVDF thin films obtained from Measurement Specialties, Inc.:

- First a lumped compact equivalent circuit compatible with commonly used Integrated Circuit software design is obtained and validated. The different components are defined by the material and geometrical parameters and by the mode shapes of the vibration transmission.

- Secondly a validation of an actuator (l=29e-3m, w=4e-3m, h=110e-6m) modal equation for the first 3 natural frequencies shows a good correspondence between the theory and the experimental results (theo: 63Hz, 402Hz, 1.12KHz ,exp: 61Hz, 380Hz, 1.06KHz).

- Thirdly, assuming the viscosity as the unique loss term, give us a proper approximation on the maximum displacement at the first resonance mode (theo: 900um, exp: 855um). The viscous term is experimentally measured for each PVDF, due to the process of fabrication we obtain different values for each one of them.

- Finally a model scalability validation is presented by the measurements of different size actuators (l1=29e-3m, w1=4e-3m, l2=18e-3m, w2=10e-3m, l3=17e-3m, w3=4e-3m) obtaining the first resonance frequency increasing (PVDF1: 61Hz, PVDF2: 162Hz, PVDF3: 183Hz).

The PVDF model validation allows us to determine the performances of the I-SWARM small leg expecting a maximum velocity of each robot ,working at it's resonance frequency, of about 1mm/s.

6166-29, Session 7

Adaptive wavelets applied to smart structures in astronomical adaptive optics

K. J. Jones, Rice Univ.

Adaptive wavelets have great potential for optimizing performance in Smart Systems. Adaptive wavelets are important when signals or environments are changing in time. Of particular interest is using adaptive wavelets in astronomical adaptive optics systems. The most advanced design for Adaptive Optics is ground based telescopesin Steward Observatory's 6.5 m MMT (Multiple Mirror Telescope) which uses three-axis PZT actuators for its Deformable Mirrors. Adaptive wavelets are expected to enhance performance in this very complex design.

Stewart Observatory's 6.5 m MMT telescope has a unique design: the Deformable Mirror (DM) is both the secondary mirror of the Cassegrain telescope and the Deformable Mirror of the Adaptive Optics system. The DM consists of 336 voice coil actuators that push on 336 small magnets glued to the backsurface of the thin 642 mm asheric ULE glass 'shell'.

A 512-segment DM has each segment glued to a three-axis PZT actuator giving 1500 degrees of freedom. The DM bimorph is a sandwich of piezo-electric material oppositely poled so that when an electric field is applied across the sandwich, one layer shrinks while the other expands creating an induced cruvature. Actuators are arranged in a circular symmetric pattern and have tens of microns of stroke. This complex design has a multitude of problems with alignment, vibrations and abberations, but it is by far the most advanced design for Adaptive Optics.

Adaptive wavelets will be applied to achieve higher resolution, greater sensitivity and faster response time to a model element of the PZT actuators which form the basis of the MMT's Adaptive Optics system. Adaptive wavelets are useful when the environment is changing with time which is the case when the Adaptive Optics senses and corrects the atmospheric distortion. Certain wavelets, i.e. 2-D CWT curvelets, may be uniquely suited for the circularly symmetricly arranged actuators.

Actuators for the Adaptive Optics systems of the MMT telescope have 10's of microns of stroke and a sensor which measures displacement at 40 kHz. An adaptive wavelet system will be developed to enhance peformance of one model PZT element of this system. Higher resolution may be possible improving Adaptive

Optics performance

6166-31, Session 7

Removal of noise from vibration data using wavelet denoising and damage classification of structures using wavelet transform and neural network (ANN) identification

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An integrated method for removal of noise form noisy vibration data and damage detection of structures using the vibration response, wavelet transforms and artificial neural network has been developed. When structural vibration response signals in time domain are decomposed into multiple sub-signals using wavelet transform, change corresponding to structural damage in each sub-signal may show notable difference, and some of the sub-signals may posses high sensitivity to small damage in structure. In this study vibration responses are denoised using soft thresholding of detail coefficient. A mixture of Stein's Unbiased Risk Estimate (SURE) and Fixed form threshold is used as a threshold selection rule. Denoised responses are then decomposed into various sub-signals using discrete wavelet transform and energy of each sub-signal in a given time-interval is calculated to quantify variations in the sub-signals caused by the structural damage. Damage feature vectors are constructed from the energy of decomposed sub-signals. ANN is used to map the relationships between damage feature and structural damage status. Damage status includes damage location as well as damage extent. This methodology has been applied on ASCE (American society of civil engineers) Structural Health Monitoring (SHM) benchmark problem. Results indicate that the proposed method can be used to remove noise associated with vibration response and detect damage status.

6166-32, Session 7

Implementation of wavelet transform based image compression using Altera's max plus II and EPF10K70

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An important characteristic of configurable computing systems is the ability to perform several functions using a single architecture, an idea captured by the term versatility. In this paper, authors got the compression results using Altera's Max PLus II software and have implemented on EPF 10K70 FPGA chip. For downloading the design, ByteBlasterMV downloadable cable has been used, which is a hardware interface to a standard parallel port. The wavelet compression algorithm is accomplished through a sequence of steps that transform grayscale images in "PGM" format into a compressed format. External memory HM628512 has been interfaced with the FPGA chip, in order to have sufficient memory for the original image. The coding has been done on VHDL platform, in which SRAM controller has been used as a component. Authors have got the good results as now the original image of any size can be taken for compression purpose, depending upon the external memory interfaced. Authors have also verified the same work on Texas Instrument's TMS320 6711 floating point DSP processor, and observed that for these applications, the results obtained with FPGAs are much better as compared to that with DSP processor.

6166-33, Session 7

Damage detection in multiwire strands by discrete wavelet-based outlier analysis and embedded guided ultrasonic waves

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This paper describes a method based on novelty detection and Discrete Wavelet Transform for damage detection. A statistical discordancy test is used to determine the presence of outliers in a set of features extracted from the Discrete Wavelet Transform of ultrasonic guided-wave signals; the outliers indicate a faulty condition of the structure under investigation. The proposed approach, which is demonstrated to be general, is applied to the quantitative detection of notch-like defects in steel strands used as cable-stays or prestressing tendons. The effect of the number of features and the effect of the ultrasonic noise level on the sensitivity of the method to the presence and the size of the defects are discussed.

6166-34, Session 7

Adaptive time-frequency analysis method for the analysis of dispersive elastic waves

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Although conventional methods such as the short-time Fourier transform (STFT) and the continuous wavelet transform (CWT) have been effectively used for the analysis of dispersive elastic waves, rapidly varying wave signals may not be accurately analyzed by these methods. Because the time-frequency tiling of conventional methods do not take into account dispersion phenomena, it is often difficult to trace accurately the time-frequency varying feature of the signals. The objective of this work is to develop advanced adaptive time-frequency analysis methods whose time-frequency tiling is varied to the dispersion characteristics of the signal to be analyzed. More specifically, a method called, "the dispersion-based short-time Fourier transform (D-STFT) and the dispersion-based continuous wavelet transform (D-CWT)" are newly developed. In these methods, each time-frequency tiling is adaptively rotated in the time-frequency plane depending on the estimated local dispersion rate of a wave signal. Since the dispersion relationship is not known in advance, an efficient procedure to extract information on the dispersion relationship hidden in a wave signal must be devised. In the proposed approach, the dispersion relationship is estimated iteratively from the ridge analysis of the result by the proposed adaptive methods where the initial estimation is based on the result by the standard methods. To verify the validity of the present approach, the Lamb waves measured in an aluminum plate were considered. Indeed, the present D-STFT and D-CWT extracted the time-frequency characteristics of wave signals more accurately than the standard STFT and CWT.

6166-14, Poster Session

Development of MR rotary suspension system for field robot

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The field robots doing autonomous driving have the mission obstacle avoidance or overwhelming. But as driving off-road, the shock and vibration effects transmitting from road profile are falling down the performance of world map modeling and obstacle recognition.

To do solve these problems, generally field robots are built assemble anti-shock and anti-vibration equipment to sensors and computers, or active or semi-active suspension equipments. These systems are to do minimization of vibration effects transmitting from road profile. And some researchers are studying the intelligent wheel mechanism for overwhelming obstacles like as if step, gap, and crevasse etc.

In this paper suggest MR rotary suspension system of field robot. This system has semi-active and 360 degree rotary suspension system.

The control criterion of suspension system is sky-hook control and the main power source supply piston actuator. And the rotating torque and angle are controlled the MR valve mode

6166-61, Poster Session

Instant-hot electrothermal water temperature control system based on PIC16C72

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The Instant-hot electrothermal water temperature control system (IEWTCS) utilizes the method of high-power to heat to improve rapidly a temperature of water, and utilizes the closed-loop control system to carry on the temperature control according to temperature of settling. The paper adopted fuzzy logic control algorithms which realized IEWTCS, and utilizes thermal resistor to detect the system temperature of output of water, according to the difference of the system temperature of output of water with settling water temperature and the difference at any time implements the difference values of temperature fuzzy logic control. Last output through regulating coherence and broken rate of the power relay contact realized the heated controls of electric power, thus achieved to constant temperature. For lowering costs, temperature control detection utilized negative coefficient of temperature of thermal resistor values with temperature change to realize temperature detection. Its distinguish ratio reach 1°C, its control's precision reach ±2°C.Thus it satisfies with IEWTCS. The circuit export of temperature detection device is corresponding to the direct currents voltage of electric heat water temperature control system, from PIC16C 72 (utilized ch0 of A/D), it transfers and exports 00H-FFH(the binary scale data codes) at inside 8 bits A/D. It utilized PIC16C72's contrast form in the memory and tried to achieve real-time temperature value according to this one, according to last time the real-time temperature value that samples and tries to achieve the real-time temperature value this time that tries to achieve with sampling, then it is used in the two input precision quantity of the fuzzy logic controls: First, the difference value(δT) of the sampling values with the value that settles temperature, second, the speed (δT/δt) that this difference value changes at any time. For resisting 50Hz interfere frequently, become

the export direct current voltages of temperature transition were sampled, it should gather 64 times in succession. Its sample time should been designed the integer times of 50 Hz periods, then gained sample average value of 64 times deserving sampling values, It can filtered the mass interferes and reserved frequently at 50 Hz. This average value is used as the sample of a temperature value, and participated in follow-up operation and disposal. This fuzzy logics control procedure changed a little, namely move up to other control systems.

6166-63, Poster Session

A semi-analytical finite element model for the analysis of piezolaminated cylindrical shells

C. M. Mota Soares, Instituto Superior Técnico (Portugal)

The development of a semi-analytical finite elçement model is presented for the analysis of culindrical shells under general loading.

The dispacement field is expand in the circumferential direction and the electical potencial by Fourier Series, considering symmetric and anti-symmetric terms.

The performance of the model is discussed through benchmark examples for static and dynamic situations.

6166-64, Poster Session

Experimental study on semiactive control of frame-shear wall eccentric structure using magnetorheological dampers

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Magnetorheological damper (MRD) is a kind of intelligent actuator, which shows immense potential in the field of structural vibration control. In order to study the dynamic characteristics of the frame-shear wall eccentric structure under earthquake and the control of the coupled translation and torsion response using MRD, the shaking table experiment was carried out.

The construction and mechanical behavior of MRD are introduced firstly, and then a new mechanical model-double-sigmoid is proposed based on the experimental study of MRD. The outstanding features of the proposed model are the consideration of the magnitude of control current and a wide range of excitation conditions. Also the identification of parameters is relatively easy, and the physical concept of the model is clear. By comparing with experimental data under different excitation conditions (frequency and amplitude), the results revealed that the proposed model could accurately describe the hysteresis nonlinear properties of MRD.

The simulation system of MRD and the 3-floor frame-shear wall eccentric structure was built according to the coupled translation and torsion response control using MRD, based on Matlab/Simulink software environment and hardware/software resources of dSPACE. This paper introduces dSPACE Real-Time simulation platform and its software environment which includes RTI and ControlDesk. It expatiates on the developing steps of control system which based on dSPACE. It is more convenient, efficient and accurate than traditional methods.

The shaking table experiment of the structural model was implemented by using rapid control prototyping (RCP) technology. The experimental results show that the coupled translation and torsion response is significantly mitigated, and the location of the MRD has an important effect on the results. The experimental environment is efficient.

6166-65, Poster Session

Adaptive blind system identification for leak detection and location in the water distribution system

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The vibration acoustic signals separately collected on pipelines are used for pinpointing a leak or leaks in buried pipelines. It may contain leak noises emanating from leakage in pipeline. However, because of the complexity and the heavy corruption with ambient noises, it is essential to use an appropriate signal model and analysis method to extract leak signals and specify leak locations. Because of the distinct acoustic channel performances, the modification on the leak noises by tubular propagation is not the same for different acoustic paths, and the leak signals picked up by separately sensors installed on either side of the leak position may alter. The features of leak signals vary with the materials, the sizes and the inbuilt conditions of tubular pipes. So it is difficult to pre-determine the knowledge of the leak noises. An adaptive blind system identification strategy is applied to estimate the transmission performances of the two acoustic paths associated with the two sensors and leak source. The relative time delay of arrival can be extracted from the transmission performances, and the attenuation factor due to the propagation of the leak source signal traveling from the leak point to the sensors is also determined.

With the time delay estimation-based source localization algorithm, the time delay of arrival is used to estimate the leak source location with the knowledge of the detection length of buried pipe between the two sensors. However, because of the distribution complexity and the inbuilt variety of the buried pipelines, the length between the two sensors is inaccessible as usual. A new location algorithm without a priori knowledge of the length of pipeline is needed. As the attenuation factor representing the propagation loss is a function of the ratio of distances between the observed and the leak source. The location can be calculated based on an algebraic relationship between the time delay, the attenuation factor, and the propagation velocity of acoustic signal in the pipe.

On the other hand, spatially separately installed sensors may simultaneously pick up an acoustic source, other than a leak, emanating from inside or outside a pipeline. The signal components from the identical source are indeed correlated. A relevant time delay between the components can be acquired. If the time delay is within the detection range, a location can be acquired. But the location can't tell whether it is a leak or not. By integrating the time delay with the relative attenuation factor, the information to distinguish the real leak has been yielded.

In this paper, the principle of the proposed scheme is discussed in detail and the corresponding algorithm is developed and used process quantity of data collected on practical engineering pipelines. The results show the validness of the proposed scheme.

6166-66, Poster Session

Nonlinear controls influence functions in an aircraft dynamics simulator

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In the development and testing of novel structural and controls concepts, such as morphing aircraft wings, appropriate models are needed for proper system identification. Both structural and aerodynamic characteristics are important in the development of these models. In most instances, available system models are not sufficient to define morphing structures but may be modified to some degree to achieve a compatible system. The objective of this study was to apply wind tunnel data collected for an Uninhabited Air Vehicle (UAV), that implements trailing edge morphing, to create a non-linear dynamics simulator, using well defined rigid body equations of motion, where the aircraft stability derivatives change with time. The aircraft, a former US Army target drone classified as the FQM-117B, modified, housed, and flown at NASA Langley Research Center, implements segmented trailing edge flaps to achieve trailing edge morphing for advanced control law development and testing. An analysis of this wind tunnel data, using data extraction algorithms, was performed to determine the reference aerodynamic force and moment coefficients for the aircraft. Further, non-linear influence functions were obtained for each of the aircraft's control surfaces, including the sixteen trailing edge flap segments. These non-linear control influence functions are applied to the aircraft dynamics to produce time varying aircraft stability derivatives. Using well-defined rigid body equations, the aircraft's aerodynamic coefficients, statistical damping derivative models, and these control influence functions, a non-linear dynamics simulator has been developed for the drone aircraft. Time domain analysis of the aircraft motion, trajectory, and state histories may be performed using these non-linear dynamics. Perturbations were introduced into the control inputs and aircraft dynamics and visualized using a 3-dimensional aircraft model. Linear models were also extracted to facilitate frequency domain analysis of the system and for control law development. The results of this study are useful in similar projects where trailing edge morphing is employed and will be instrumental in the University of Maryland and NASA's continuing study of active wing load control.

6166-67, Poster Session

Thermal and acoustic management using multiple on-die thermal sensors and multiple fans in high-performance computer platforms

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A typical high performance PC has at least three fans: one for the power supply, one for the CPU and one for the graphics card. The CPU fan is normally integrated with a heat sink that is attached to the silicon through a spreader plate, with thermal interface material applied between the contact surfaces to enhance heat transfer. This so called active heat sink, where the fan controls the thermal resistance of the cooling solution, is sometimes ducted directly to the ventilation apertures at the back or at the side of the chassis. The other major component of a PC that increasingly features an active heat sink is the graphics card. The power supply fan provides most of the airflow to cool the remaining parts of the system by pulling air from the outside through the venting areas of the chassis and discharging it back to the outside, hopefully after it flows over the key electronic compo-

nents, i.e., the “hot spots” of the system. The greater the air velocity over a component, the greater is the heat transfer from that component; hence a power supply with the greatest airflow possible is normally used. Fans generate acoustic noise in a cubic relation with fan speed; they also tend to fail due to wear-out and other causes more frequently than the electronic components they are intended to protect. Moreover, typical air cooling thermal solutions are approaching physical limits given cost and size constraints and with ever increasing power densities, modern microprocessors must implement thermal management policies at the micro-architectural level to self-protect from excessive heat generation. This ensures system reliability at the expense of maximum performance. Modern motherboards feature hardware monitoring to protect system components and alert users about abnormal operating conditions. Fan speed control through an embedded ASIC is also possible based on instantaneous temperature readings from a temperature sensor that is typically located right on the CPU. In the present work we report results of using a thermal and acoustic management scheme based on non-linear, adaptive control of multiple system fans using input data from multiple on-die thermal sensors. The aim of this study is to contribute towards extending the use of air cooling solutions in modern high performance computer platforms.

6166-68, Poster Session

Experimental validation of an active eddy current vibration control scheme

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Eddy currents are induced when a conductive material is subjected to a time changing magnetic field. These eddy currents can be formed through several different methods, including motion of the conductor in a static field or variation in the strength of the magnetic field relative to the conductor. Once the eddy currents are formed they circulate inside the conductor resulting in a magnetic field. The field generated due to this circulation interacts with the applied magnetic field producing a force. However, this force is dynamic and will only be present for a short period of time due to the internal resistance of the conductive material which causes the eddy currents to be dissipated. This manuscript will study the use of an electromagnet with a time changing current applied to it in order to induce eddy currents in the structure. By actively controlling the current flowing through a coil based on a sensor signal, the strength of the magnetic field is controlled as well as the density of the eddy currents induced in the conductor. The model of the eddy current vibration control system has been developed in a previous manuscript and will therefore only briefly presented. Using the model of the system experiments will be performed on a cantilever beam in order to validate the models accuracy. It will be shown that the model can accurately predict the dynamics of the beam with the electromagnetic control system and that significant vibration control can be achieved.

6166-69, Poster Session

Optimum sensor placement on damage detection of long-span bridges

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Damage detection is the core technique of bridge health monitoring systems. Mostly, the detection is based on comparison of initial signatures (frequency, mode shapes and so on) of intact bridge with that of damaged bridge. To identify the damage in time, the problem of sensor placement is the key factor.

In this paper, three optimum sensor placement algorithms based on EI (Effective Independence), MAC (mode assurance criterion) matrix and the fisher information matrix are used. The study begins with a detailed finite element model of Wenhui cable-stayed bridge. The choice of the minimum number of coordinates is estimated by Kammer DC’s theory of model error effect on sensor placement.

Comparing the four criteria (MAC, mode energy, condition number and fisher information) value of these two methods, this paper suggests where the suitability of the chosen locations can be assessed.

6166-71, Poster Session

Comparison of collocation strategies of sensor and actuator for vibration control of smart structures

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The problem considered in this paper is about the collocation strategies of sensor and actuator for the active control of sound and vibration. It is well-known that a point collocated sensor-actuator pair offers an unconditional stability with very high performance when it is used with a direct velocity feedback (DVFB) control, because the pair has strictly positive real (SPR) property. In order to utilize this SPR characteristics, a matched piezoelectric sensor and actuator pair is considered, but this pair suffers from the in-plane motion coupling problem with the out-of-plane motion due to the piezo sensor and actuator interaction. This coupling phnomenon limits the stability and performance of the matched pair with DVFB control. As a new alternative, a point sensor and distributed piezoelectric actuator pair is also considered, which provides SPR property in all frequency range when the pair is implemented on a clamped-clapmed beam. The use of this sensor-actuator pair is highly expected for the applications to more practical active control of sound and vibration systems with the DVFB control strategy.

6166-72, Poster Session

Construction of digital shadow moire images for the analysis of bending vibrations of a plate

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The problem of bending vibrations is common in different engineering and physical applications. Bending vibrations of centrally clamped rotating circular disks play crucial role in functionality of hard disk drives. Lots of efforts are spent for dynamic stabilisation, control and measurement of bending vibrations in such micromechanical systems. Nevertheless, measurement of microscopic deflections from the state of equilibrium is a challenging problem. Different optical measurement techniques are developed for experimental investigation of bending vibrations. Shadow moire is one of the popular methods for experimental analysis of bending vibrations of structures. Unfortunately, interpretation of experimental measurement results is a nontrivial inverse engineering problem often having non-unique solutions. Therefore there exists a definite need for hybrid numerical - experimental techniques that could help to interpret the measurement results. The procedure for the generation of digital stroboscopic shadow moiré images for the eigenmodes of bending vibrations of a plate is developed. It is based on the methods of computer graphics and the method of finite elements for the analysis of bending vibrations of a plate. The construction of digital shadow moire images builds the ground for hybrid numerical-experimental procedures and enables to analyze the experimental results with greater precision.

6166-35, Session 8

A multidimensional thermomechanical model for pseudoelastic response of SMA

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It has been shown by experiments that the stress-induced transformations in NiTi shape memory alloys are inhomogeneous in nature and can result in localized deformation. It has also been shown that the complex coupling that exists among stress, temperature, and the rate of heat generation during stress-induced phase transformations can affect the pseudoelastic behavior of SMAs. In the present work, a multi-dimensional thermomechanical model is developed in order to simulate the localized phase transformations and propagation of transformation front(s) in SMA materials. The model is a generalization of the one-dimensional model previously developed by the authors, which consists of a constitutive relation, a nucleation criterion, and a transformation evolution rule (kinetic relation). The constitutive relation is constructed based on the continuum mechanics principles and generalized plasticity, which relates the increment of total strain to those of stress and martensitic fraction. The nucleation and kinetic of transformation for both the forward and reverse transformations are expressed in terms of a set of transformation surfaces defined in the stress-temperature hyperspace. It is assumed that the stability of a phase at any instant is determined by a potential function of stress, temperature, and martensitic fraction, which forms a surface in the stress-temperature hyperspace. During the forward (or reverse) transformation, the stress-temperature vector in this space moves from a higher (or lower) level of energy towards a lower (or higher) level of energy. The path that is traveled by this vector is governed by the kinetic equation and appears in the form of an incremental relation among stress, temperature, and martensitic fraction. Therefore, the model allows for the determination of phase transformations induced solely by mechanical loading, change in ambient temperature, or simultaneous mechanical and thermal loading. The dynamic behavior of a NiTi strip and a beam at various loading rates are simulated by using the finite element method and the current model. The thermomechanical coupling among the transformation stress, latent heat of transformation, and heat exchange with the ambient medium are considered thus allowing the model to capture the strain rate effects. Some of the interesting features of the simulated responses related to the damping capacity and cyclic effects are highlighted.

6166-36, Session 8

Application of one-dimensional phase transformation model to tensile-torsional pseudoelastic behavior of shape memory alloy tubes

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The one-dimensional phase transformation model proposed by Ikeda et al. [2004 Smart Mater. Struct. 13 916-925: 2004 Proc. SPIE 5383 112-121] was applied to tensile-torsional pseudoelastic behavior of shape memory alloy (SMA) tubes. Comparison of numerical simulation with available experimental data [Helm and Haupt 2001 Proc. SPIE 4333 302-313] confirmed that this model could capture the tensile and torsional pseudoelastic behavior quantitatively.

The one-dimensional phase model is a kind of the continuous macroscopic models, which was derived by mathematically increasing number of grains to infinity on a grain-based micromechanical model [Nae et al. 2003 Smart Mater. Struct. 12 6-17: Ikeda et al. 2003 Proc. SPIE 5049 35-45]. In this one-dimensional phase model, the virtual grains are sorted in order of energy required for transformation due to the internal friction between the grains and the phases. The order of the grains is assumed to be unchanged irrespective of the phases before and after transformation. Accordingly, the transformation can be considered to take place in the one-direction along the grains sorted one-dimensionally. The previous name of this model was the shift-skip model because minor loops were drawn by shifting and skipping a major loop. This model was applied to a uni-axial tensile-compressive asymmetric pseudoelastic behavior [Ikeda 2005 Proc. SPIE 5757 344-352]. There three phases were considered, namely, an austenitic phase, a tensile stress induced martensitic phase, and a compressive stress induced martensitic phase. Stress-strain hysteresis loops for a SMA bar under tensile-compressive cyclic loading were simulated and the obtained result showed that the model could well capture the asymmetric stress-strain loops for tension and compression, minor loops, and effects of temperature and strain rate.

In the present paper, this one-dimensional model was applied to bi-axial tensile-torsional pseudoelastic behavior. The tensile-torsional pseudoelastic behavior can be also simulated by micromechanical models. However, their results are rather qualitative and these calculations are time-consuming. Hence, a simple yet accurate model would be useful for the analyses. Here a torsional stress induced martensitic phase was considered additionally. The tensile and torsional stress-strain hysteresis loops for a pseudoelastic SMA thin tube were simulated. The simulated loops were in quantitative agreement with the experimental data for both the tension and torsion. Then the values of the material constants were easy to be determined. However, for combined loading, it was not easy to determine those, because some constants for tension affected the torsional deformation behavior, and vice versa. To find a way to determine those values is a future work.

6166-37, Session 8

Improved one-dimensional constitutive model of superelastic shape memory alloy wires

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The superelastic shape memory alloys (SMAs) have been increasingly used to provide passive damping in various applications. Modeling of SMAs' thermomechanical behavior has been an active area of research. The exsiting models are generally valid only for quasi-static loading conditions, and the formulations with many difficultly measurable parameters are extremely complex for practical use. Graesser modified Ozdemir's one-dimensional hysteretic model to include the macroscopic characteristics of SMAs. Except for the relative simple formulation and easily acquired parameters, Graesser's phenomenological model can approximately express the effect of loading rate on the hysteresis without considering the complex mechanism of phase transformation. However, Graesser's model uses the identical elastic modulus during the loading and unloading branches, so its prediction is not a nice match for the experimental result and it over-estimates the material's absorbing energy. Therefore, it is necessary to improve Graesser's model according to the experimental results. First, displacement controlled cyclic loading tests of superelastic Ni-Ti uniaxial specimens are conducted under isothermal conditions on electron equipment. The investigation concerns the effects of strain levels and loading rates on the material response. Diversified strain levels are used in the experiments, ranging from 1% to 6% with intervals of 0.5% strain. The tests are carried out at various displacement rates, such as 3mm/min, 15mm/min, 35mm/min, 60mm/min and 80mm/min, but the displacement rate keeps constant through each cycle. Second, the hysteresis behavior of Ni-Ti is studied in mathematic methods. The experiments not only show the evident difference of the slopes between the loading and unloading phases, but also indicate that the unloading's slope decreases with the strain level increasing. The yield point where the transformation from the parent phase to martensite starts doesn't show a pronounced sensitivity to the loading rate. But the higher loading rate can increase the phase transformation course's slope (i.e., the inelastic branch' s slope) and decrease the unloading's modulus, which affects the shape of the hysteresis and the material's energy dissipation. By least-square method, two formulas are set up. One expresses the relation between the slope of unloading branch and strain level (or internal variable) at varying loading rate, the other describes the developing trend for the inelastic slope to loading rate. Third, Graesser's model is improved and the corresponding procedure is finished. On the base of Graesser's model, the improved model divides the full cyclic course into two parts, such as the loading part and unloading part, and each part adopts its respective elastic modulus and inelastic slope. Some parameters can be easily chosen according to the testing data. The MATLAB program is compiled to calculate the improved model employed fourth-order Runge-Kutta Forward integration. Finally, Several numerical simulations are given. The issues addressed in this work include the comparisons of model predictions to the experimental responses for different strain levels and loading rates. Some conclusions can be drawn that the improved model can predict the cyclic hysteresis consistent to the experimental results, and the model can capture the details of mechanical behavior of SMAs more accurately than Graesser's model.

6166-38, Session 9

Use of a piezo-driven cantilever beam as a sensor for electrostatic voltmeter

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In this paper authors examine the design and implementation of a cantilever beam-style probe for non-contacting electrostatic voltmeter. The beam is driven by a piezoelectric actuator with a feedback loop controlling amplitude of the electrostatic sensor displacement. Choice of the vibration mode and placement of the actuator and sensor are discussed. A simple model for the first three natural frequencies of the beam is constructed and compared with the experimental results.

6166-39, Session 9

Numerical comparison of patch and sandwich piezoelectric transducers for transmitting ultrasonic waves

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Guided wave ultrasonic inspection is becoming an important method of non-destructive testing for long, slender structures such as pipes and rails. It is possible to inspect or even monitor large lengths of the structure using stationary transducers. In this case it is desirable to use transducers that can strongly excite a specific mode of wave propagation in the waveguide.

Piezoelectric patch transducers are frequently employed, by researchers, for exciting waves in beam like structures. The piezoelectric patches can be attached to both sides of the beam and driven in phase or in anti-phase they can excite longitudinal or bending waves. Sonar systems frequently make use of resonant transducers, such as sandwich transducers, for acoustic wave generation and this principle has been used to excite a rail. This paper compares the two transduction approaches, for launching waves in constant cross-section waveguides, by numerical modeling.

A general modeling method should be applicable to any configuration of transducer and any cross-section of waveguide. Analytical solutions exist for simple cross-sections but more complex waveguides require numerical modeling by methods such as the finite element method. The excitation of waves in waveguides may be analysed in the time domain using conventional finite element methods. This analysis is computationally very demanding as the model must be a number of wavelengths long to avoid the influence of reflections from the ends of the model. In addition, separating the contributions of the individual modes of propagation can be difficult. In this paper an alternative approach is employed, which allows direct computation of the frequency response of the transducer attached to the waveguide. The waveguide is modelled using specially developed waveguide finite elements, which are formulated using a complex exponential to describe the wave propagation along the structure and finite element interpolation over the area of the element. This requires only a two-dimensional finite element mesh covering the cross-section of the waveguide and provides a very efficient analysis of the free wave propagation in the waveguide. This model can be used to compute the response of the waveguide to harmonic forces. The response of the waveguide to forces at the nodes which are in contact with the piezoelectric transducer can be computed to produce a dynamic stiffness matrix (complex and frequency dependent) representing the waveguide. This matrix is included in a model of the piezoelectric transducer developed using conventional three-dimensional piezoelectric finite elements. The response of the piezoelectric transducer (attached to the waveguide) to electrical excitation is computed and the displacements at the interface degrees of freedom are used to compute the forces applied

to the waveguide and hence the waves excited in the waveguide.

This modelling method is applied to patch and sandwich type transducers for producing longitudinal and bending waves in rectangular waveguides. Rules for a meaningful comparison are established and performance measures defined. Finally conclusions are drawn as to which type of transducer is better for which application.

6166-40, Session 9

High displacement nonlinear asymmetrically designed piezoelectric actuators

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As the application of piezoelectric elements in aeronautics is expanding continuously, new types of structures are necessary in order to support this trend. The need to use the piezoelectrics' full potential, has led to the design of new class of actuators [1], [2], [3] which although are based on conventional pzt materials, they seem to get rid of the inherent drawback of these elements, namely, the force/displacement trade off that someone has to deal with for the elaboration of a functional actuator. Non-linear dynamics are entering the stage creating a new area of research on large displacement pzt actuators. A number of researchers [4], [5] have addressed already the theoretical aspects of non-linear mechanics for piezoelectric actuators.

As it has been shown already in [1], post buckling behavior of pzt actuators can be very promising regarding the displacement behavior of such actuators. Experiments have shown that by increasing the compressive force, the displacement response is enhanced. However, there are limits on this procedure taking into account the fragile behavior of pzt elements as well as depoling problems that may occur due to high stress levels. In any case these arrangements are a clear evidence of the potential that exists in non-linear mechanics if they are used in a proactive way.

In the present work this concept goes one step further. Instead of using continuous pzt elements over a thin metallic substrate and covering the whole length of the actuator, a new configuration is proposed. The pzt elements are much smaller and cover only a small part of the actuator and this is done in an asymmetrical pattern. The pzt elements cover only the areas of the actuator very close to the edges. Although the quantity of the active material is much less, the result is not proportionally smaller. This configuration permits the excitation of the second buckling mode of the actuator leading in higher displacements and even to snap-through buckling in the extreme case.

This issue is tackled both theoretically and experimentally. An analytical formulation is presented in order to derive the critical buckling load and also the post buckling behavior of the actuator implementing CLPT since thin structures are considered. Additionally the displacement of the actuator is examined for different positions of PZT layers keeping constant their dimensions. Experimental verification is performed through compression tests. The buckling of the piezoelectric actuators is displacement driven and the distance between the two edges of the actuator is kept constant. A very sensitive load cell is placed on the edge of the actuator and once the buckling occurs, the pzt elements are actuated. It is thus possible to measure the change on the compressive force exerted on the actuator due to the action of the pzt's and compare it with the theoretical results. The out of plane displacement is measured using a laser sensor so that there is no influence on the buckling behavior of the structure due to a contact measuring device like an LVDT. Additionally the blocking force of the actuator is examined with respect to the vertical distance between its edges. The higher the compression, the higher the blocking force of the actuator; however, this is examined with respect to the maximum stresses that the pzt elements can withstand and also with respect to the displacement that the actuator can provide. It is thus obvious that for specific geometric characteristics, there is an optimum compression of the actuator that can provide the best trade off between displacement and blocking force.

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6166-41, Session 9

Dynamic analysis of a pressure sensor diaphragm coupled with an air-backed cavity

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In this paper, recent efforts conducted to investigate the dynamic behavior of a pressure sensor diaphragm coupled with a cylindrical air-backed cavity are presented. Our study shows that a careful consideration of the coupling effect between the plate and the air-backed cavity is necessary to understand many design parameters of a pressure sensor, such as sensitivity, bandwidth, and dynamic range. A coupling parameter is determined to serve as an indicator of the coupling strength. For a strong coupling case, the model predictions in terms of diaphragm center displacement and natural frequencies based on the linear analysis of the coupled system are found to be significantly different from a pure plate model. The nonlinear analysis of the coupled system shows that the nonlinear effects limit both the sensor bandwidth and the dynamic range. These analyses and results would be valuable for carrying out the design of small pressure sensors (e.g., MEMS pressure sensors) for various applications.

6166-42, Session 9

Modeling and fuzzy control of ER damper using higher order spectra

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The damping force of the semi-active suspension system using ER fluid is controlled by the magnitude of applied voltage. Therefore, a mathematical model of the ER damper is very useful for the design of the ER damper device which consists of a control unit and dynamic weights.

In this paper, we obtained nonlinear model of ER damper by analyzing the frequency coupling between damper speed signal (input) and damper force signal (output).

We applied a FLC (Fuzzy Logic Control) algorithm to the obtained nonlinear model to improve tracking performance of the required damping force.

We also controlled the overall suspension system of the quarter model, which uses the applied voltage as an input, using a fuzzy sky-hook control algorithm tuned by SOC (Self-Organizing Control) algorithm.

2 DOF (Degree Of Freedom) quarter car experimental system is used to obtain nonlinear model of ER damper. It consists of a tire, an unsprung mass, a spring, an ER damper and a sprung mass.

Hydraulic servo system is used to excite 2 DOF vibration systems and control flow of servo valve using feedback signal of LVDT, which is installed in hydraulic cylinder. And then, amplitude and frequency of excitation signals are controlled by flow.

Sprung mass and unsprung mass move vertically along guide rail and position of masses are measured by LVDT. Therefore, the displacements of mass by excitation are measured.

Load cell, which can measure damping force directly, is installed in ER damper and high voltage power supplier applies electric field to ER damper. High voltage supplier is implemented to amplify 0~5V computer output voltage to 0~5kV high voltage and its maximum output current is 10mA.

High order spectrum analysis method, which is used to obtain nonlinear model of ER damper, offers information of frequency coupling and can analyze existence of nonlinearity. Therefore we can obtain information about the modeling of the damper by analyzing the frequency coupling between damper speed signal and damper force signal.

And by use of higher order spectra analysis method, nonlinear characteristics of ER damper are analyzed. It shows the existence of nonlinear 2nd and 3rd-order order terms.

Using the experimental system, 2Hz mono-frequency is used for excitation of ER damper and the damping force is measured by load-cell.

From the obtained bispectrum, bicoherence, trispectrum and tricoherence, we can confirm that frequency coupling of 4Hz and 6 Hz is produced by 2 Hz excitation frequency signal.

Based on the higher order spectrum analysis results, we can represent the damping force model as higher order function with 3rd-order nonlinear term.

The 1st order coefficient of the proposed damper model is linearly varied according to the variance of applied electric field. The 2nd order coefficient is rapidly changed between 1kV/mm and 2kV/mm. But 3rd-order coefficient is decreased at the range over 2kV/mm.

From the comparison of the calculated damping force by least-square method and measured damping force from experimental system, we confirmed the proposed nonlinear model of ER damper can be used as a mathematical model of the ER damper.

Skyhook control method of suspension system uses damping force as a system output.

In the case of suspension system with ER damper, damping force is adjusted by the applied voltage of ER damper duct. Therefore a suitable controller is necessary in order to improve tracking performance of the required damping force.

In this paper, we uses fuzzy logic controller to improve tracking performance of ER damper.

Error and change of error between reference damping force and output damping force of ER damper model are used as linguistic inputs. And electric voltage, which is used in order to control ER damper, is used as a linguistic output.

The control performances of the FLC are investigated using step input, ramp input and sinusoidal input as reference damping forces. Damping force of the damper model is a function of speed. Therefore simulations are performed with various fixed speed of sprung mass.

6166-43, Session 10

Nonlinear optimal tracking control of a piezoelectrically driven nanopositioning stage

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High performance nanopositioning stages used in research applications such as molecular spectroscopy and three-dimensional nanometer-scale lithography requires stringent position control over relatively large dimensions and multiple drive frequencies. Piezoelectric materials typically employed in nanopositioning stages provide excellent position control when driven at relatively low frequency and low field levels. However, in high speed applications over micron to millimeter size envelopes, piezoelectric materials exhibit nonlinear and rate-dependent hysteresis which requires control designs that can effectively accommodate such behavior. In this work, a nonlinear, rate-dependent piezoelectric constitutive law is incorporated into the optimal tracking control design to accurately track a desired reference signal when nonlinearities and rate-dependent hysteresis are present. A comparison between linear optimal control and the nonlinear optimal control design is given to illustrate performance enhancements when the constitutive behavior is included in the control design.

6166-44, Session 10

A finite element approach for simultaneous precision positioning and vibration suppression of smart structures with PID controller

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Smart structures are combinations of structural units, sensory units, actuation units, as well as control and signal processing units so as to perform specific functions, e.g., position and/or vibration control, and have been developed rapidly due to their great potential in the fields of aerospace, civil engineering, ships, automobiles, as well as precision instruments and machines. Much attention has been paid to either vibration control or the feasibility of position/shape control of smart structures. However, smart structures with simultaneous precision positioning and vibration suppression (SPPVS) capabilities are very commom in aeroautical and astronautical engineering structures.

This paper presents a finite element approach for simultaneous precision positioning and vibration suppression of smart structures with PID controllers. The modeling, dynamic analysis, controller design, and simulations are all performed in the finite element environment, which makes the design, analysis, and control of smart structures much easier. First, a model of an active composite panel with two surface-mounted PZT patches is built and its dynamics is analyzed and experimentally measured. A PID controller is then designed to achieve the SPPVS of the smart panel subject to harmonic and random excitations. The parametric studies of the controller are also carried out for selecting the optimal controller parameters. The results indicate that the controller can meet both requirements of precision positioning and vibration suppression simultaneously; however, the overall performance is not always satisfactory. These finite element results are also compared with those from The MathWorks' Matlab — — the most recognized control code. The agreement between the two demonstrates the feasibility and correctness of the proposed finite element environment for smart structures modeling, analysis, and control design.

6166-45, Session 10

Extremum-seeking control and closed-loop quality factor monitoring for an ultrasonic/sonic driller/corer (USDC) driven at high power

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Future NASA exploration missions will increasingly require sampling, in-situ analysis and possibly the return of material to Earth for further tests. One of the challenges to addressing this need is the ability to drill using for low axial loading while operating from light weight platforms (e.g., lander, rover, etc.) as well as operate at planets with low gravity. For this purpose, the authors developed the Ultrasonic/Sonic Driller/Corer (USDC) jointly with Cybersonics Inc. Studies of the operation of the USDC at high power have shown there is a critical need to self-tune to maintain the operation of the piezoelectric actuator at resonance. Performing such tuning is encountered with difficulties and to address them an extremum-seeking control algorithm is being investigated. This algorithm is designed to tune the driving frequency of a time-varying resonating actuator subjected to both random and high-power impulsive noise disturbances. Using this algorithm the performance of the actuator is monitored on a time-scale that is compatible with its slowly time-varying physical characteristics. The algorithm includes a parameter estimator, which estimates the coefficients of a unimodal function that characterizes the quality factor of the USDC. Since the parameter estimator converges sufficiently faster than the time-varying drift of the USDC's physical parameters, the proposed extremum-seeking estimation and control algorithm is potentially applicable for use as a closed-loop health monitoring system. Specifically, this system may be programmed to automatically adjust the duty-cycle of the sinusoidal driver signal to guarantee that the quality factor of the USDC does not fall below a user-defined set-point. Such fault-tolerant functionality is especially important in automated drilling applications where it is essential not to inadvertently drive the piezoelectric ceramic crystals of the USDC beyond their capacities. The details of the algorithm and experimental results will be described and discussed in this paper.

6166-46, Session 10

An approach for adaptive drive-vibration control of lightweight machine tools

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The performance of machine tools like e.g. laser cutting machines is mainly characterized by two paramters: On the one hand high stiffness in order to shift vibrations out of the critical frequency range and thereby get high decay rates, on the other hand high speed of the tool center point to lower production time in operation. Yet, these demands are somewhat contrary, as an increase of stiffness yields high amout of moving mass and therefore limits the attainable accelerations. So far, the control system of machine tools is implemented using classical cascaded PI-controllers which can not sufficiently be adapted to the complex structural machine dynamics.

The approach presented in this paper starts with a lightweight design for the machine tool's structure (e.g. using CFRP), which allows to use the power of the drive motors in an optimal way. However, for such a lightweight design, vibrations are inevitable. This problem is compensated for, by using an adaptive model-based control algorithm which simultaneously controls both, the drive motors and a set of piezoelectric stack actuators for active vibration suppression. The input signals to the controller are position and velocity of the drives and the signals of optimally placed piezoceramic sensors attached to the structure.

For the example of a 2-D laser cutting machine, one has to deal with a two-dimensional parameter space for the controller design model. This model is generated using a grid of finite-element models for distinct positions of the tool center point in the workspace and combine these models to a parameterized continuous model using Linear Fractional Transformation (LFT) Modelling. The computed model will be used to design the integrated adaptive drive-vibration-controller. As the velocity of the parameter variations when the tool center point is moving yields additional dynamics which might lower the performance or even destabilize the system when not taken care of, a design method which can cope with fast parameter variations for high-order models must be applied. The LMI (Linear Matrix Inequations) approach provides the necessary tools for robust adaptive control while taking into account parameter variations by the Popov criterion.

6166-47, Session 10

Gain-scheduled control of a smart beam with identification of a crack

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This paper deals with damage detection and vibration control of a smart beam.

This study proposes a method for the crack identification when the vibration of the beam is suppressed by using active control. A finite element model of a cracked beam is established by applying fracture mechanics methods. This model is applied to a cantilever beam and the natural frequencies are determined for a different crack length and locations. First, we identify the crack length and locations by using the relationship between the crack and the natural frequency of the beam. However, when the vibration is suppressed by an active control, the crack length and locations is difficult to identify. This is because the natural frequency is obtained by fast Fourier transform (FFT) of the vibration data. This study propose crack identification algorithm under the vibration control where the crack detection is repeated more than once. Furthermore, we design the gain-scheduled controller considering both the crack length and the location. Once cracks are present in structures, the control performance becomes worse because both eigenvalue and eigenvector of the beam vary. A linear parameter-varying (LPV) model considering the crack length and locations is designed for the gain-scheduled controller design. To obtain the LPV model, the discrepancy between the state-space representations of the reduced-order model and the LPV model is measured by its Frobenius norm, and this norm is minimized by simultaneous optimization of the coefficient functions and the state-space representations contained in the model. The efficiencies of our crack identification method and the gain-scheduled controller design are verified by simulation and experiment.

6166-48, Session 11

Shape and vibration control of active laminated plates for RF and optical applications

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Active structures flexible enough to be molded in desired shapes and coupled with the ability to be controlled have been pursued for many high precision applications. Membrane-thin but extremely large (\>10 m) optical mirrors and reflectors for combined RF-Optical applications are one of the important high precision applications where shape and vibration control of a structure is highly desirable. In this application the precision demands of the optical surface coupled mitigates the combined benefit of the large aperture.

Polyvinylidene Fluoride or PVDF is a synthetic polymer with strong piezoelectric properties. This material is particularly suitable for making large reflectors due to its availability in thin sheets, 9 to 800 thick. Additionally, it's almost linear and nonhysteretic behavior at low to moderate operating voltages and its relative low cost and ease of manufacturability makes it a suitable material for shape and vibration control of large reflecting structures.

This research focuses on a three-layer laminated actuator with two layers of PVDF film bonded with a layer of epoxy. In this research the actuator itself will act as the RF and optical surface and therefore will require no secondary surface. This means that the orthotropic properties of the laminate cannot be neglected. The electrodes are applied externally on the PVDF film in a given pattern such that the applied electric field will yield the desired shape of the laminate. Research has been conducted for the quasi-static shape control of the laminate. Sumali, H. et. al. [1] used the simply supported laminated plate to get the desired static deflection by applying the required voltages at different places. Massad, J.E. et. al. [2] used the corner-supported laminated plate for static deflection. The quasi-static cases find it difficult to counter the external disturbances and regain their original shape. This research is aimed to minimize this problem by including the dynamic term in the laminate vibration model. Vibration control will help in retaining the shape in the presence of external disturbances.

The research specifically deals with the dynamic model of a simply supported laminated plate. The vibration model takes into account the orthotropic properties of the PVDF film and assumes the bonding epoxy to be isotropic. The top and bottom layers of the laminate are polarized in the opposite directions thus creating a moment and a case of bending in the laminate. Figure 1 shows a three layer laminate with two PVDF films bonded by a layer of epoxy.

Assuming all the layers are perfectly aligned, simply supported laminated plate equation of motion in the transverse direction can be written as,.....

Control Methodology:

Figure 2 shows a schematic of the system with controller, output ( ), reference ( ), noise , disturbance , and input to the system.

Burke and Hubbard Jr. [3, 4] used Green's function to develop a dynamic control methodology for a beam. This research will extend the methodology to plates and will use a similar idea to convert the equation of motion of the laminated plate into an integral equation.

The output of equation (1) in spatial coordinates and time domain can be given as,

To use the Green's function in the control block diagram (as a transfer function), it needs to be transformed into frequency domain and wave number. If each pair of modal numbers (m, n) can be represented by a single variable (considering each pair correspond to one natural frequency), then the transformed output of the system can be written as,

Where, is the transfer function or the transformed Green's function. From the block diagram of figure 2, the output of the system can be written as,

.....

The idea in control development is to make so that. This ensures that the output ( ) tracks or converges to the reference input. This highlights how the proposed control will force the plate to maintain a given shape. Just by inspection of equations (4) and (6), it could be seen that in the absence of external disturbance and sensor noise the above conditions could be achieved by making. To achieve this the controller needs to be fine-tuned, so that the input to the plant could be altered to get the desired result.

To distribute the controller output, the electrode is divided into grids (grid size depends in the accuracy of the final shape); each grid will get the input from the controller. If the dominant mode is uncontrollable, then the number of grids could be altered to make it controllable.

Also instead of placing external sensors to measure the deflection, grids on the PVDF film could be used as sensors. This will reduce the unknown dynamics of the external sensors.

6166-49, Session 11

Averaging and switching control for actively tuned piezostructural vibration absorbers

A. J. Kurdila, Univ. of Florida

No abstract available

6166-50, Session 11

Distributed vibration control with sensor networks

T. Tao, K. D. Frampton, Vanderbilt Univ.

The application of sensor networks for distributed vibration control of a simply supported beam is studied both analytically and experimentally. A simply supported beam is controlled by nodes within the sensor network. Each node consists of a pair of collocated sensor and actuator along with network communication. The nodes can communicate sensor information according to a predefined distributed algorithm, in order to achieve global vibration reduction. A control algorithm using direct velocity feedback, which is appropriate for distributed control, is presented in this work. When large-scale systems are considered, this scheme provides a scalable control approach due to small computation complexity. Satisfactory vibration suppression has been observed for distributed vibration control of a simply supported beam. The effects of different distributed architecture such as the reach are also demonstrated.

6166-51, Session 11

Comparison of actuators for semi-active torsional vibration control

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Three commercially available torsional actuators have been tested and analyzed to assess their applicability for use in semi-active torsional vibration control. Semi-active control of torsional vibration can be realized through the use of variable friction brakes or clutches applied to a primary system acted on by oscillating torques. A modified skyhook damping control approach can then be used such that the brakes and clutches are actuated to alternately load and release the primary system during parts of the cycle. The efficacy of this control approach is directly dependent on the authority of the particular actuator used, both in terms of bandwidth and also in terms of the maximum torque that can be generated. A dry friction brake, a magneto-rheological fluid brake, and a magnetic particle clutch were acquired and tested to evaluate the actuators in terms of their torque "on" and "off" response times, friction torque as a function of rotating speed and actuation signal, and standard bandwidth. That data was then used to create general mathematical models to predict the behavior of the different actuators when excited with different control signals. The results indicate the limitations of the

different actuators and their applicability to general torsional vibration control problems.

6166-52, Session 11

Six DOF vibration control using magnetorheological technology

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Within this work a 6 DOF vibration isolation system with semi-active control, using magnetorheological (MR) technology, is investigated. Parallel platform mechanisms are ideal candidates for 6 DOF positioning and vibration isolation. While active and passive vibration control have been extensively used in parallel platforms, a 6 DOF parallel platform which utilizes semi-active vibration control has not received as much attention. The advantages of semi-active control include reduced cost by using a simpler actuator intended for only positioning, reduced power requirements, and improved stability. Within this work, a 6 DOF parallel platform model was created. Each leg of the platform model includes an actuator for precision positioning, a stiffness element, and an MR damper. The simulations show that the platform can be used for positioning and at the same time it is able to achieve a considerable vibration attenuation that results in a clean environment for the precision steering of sensitive equipment.

6166-53, Session 11

VHDL control system for linear ultrasonic motors

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Traveling wave ultrasonic motor (TWUSM) is a promising type of position actuator that utilizes piezoelectricity for producing displacements. Nakamura presented a dynamic model for TWUSM describing its typical behavior. TWUSM slider displacement could be approximated by a first order system when accelerating and by a zero order equation when braking, depending exclusively from the friction between rotor and stator. Coefficients for both equations are found by applying an input pulse at motor's input and observing the resulting displacement. Those coefficients are different for each motor and may change in time. Thus, ultrasonic motor's optimal driving conditions may require an adaptative trimming in order to track the changes in its resonance conditions. The state machine presented in this work can predict relevant parameters of ultrasonic motors for its control.

The proposed control system implements several important features for TWUSM positioning applications, such as: identification of allowed slider displacement range; identification of instantaneous speed at each position reading; prediction of wait time to the next position reading that corresponds to a "moving" condition, or to a "stopped" condition; estimation of the stop position and the corresponding power turn-off time that leads the slider at this point; identification and updating of parameters; three displacement modes: coarse, fine, and one step, according to required speed and resolution.

The controller described in this work applies, in a general way, to any type of linear TWUSM. The adaptation of control rules to its characteristics is made by identifying some of its parameters. The system will only start to drive the motor after the first manual reset command, when it reads the encoder output and drives the slider to the most distant position inside the working range. Since the parameters of the motor are still not computed at this stage, first displacement is executed in the coarse mode. When the controller identifies the right position code, it turns off the input voltage but the axis continues to slide till it stops. The speed and acceleration values acquired during the first displacement are employed to compute an initial parameters approach. This value is used by controller to return the slider to required position, and the system is already able to operate in the fine mode, enabling its inputs for receiving external commands.

Since friction coefficient may change along the displacement range, some small positioning errors may occur, typically one or two encoder positions. For the final position approach, the system assumes "one step" operation mode. In this mode, the input pulse width for the exact positioning is determined from the parameters calculated in recent driving cycles.

The control system logic was tested with ModelSim 5.6a(c), in MentorGraphics(c) environment with a simulated linear TWUSM.

Timing diagrams describing controller inputs and outputs indicate a correct operation for every operation mode, summarizing its successful operation. Several critical situations have been simulated for different TWUSM characteristics, and the controller was always capable of positioning the slider at the exact programmed position. Thus, the positioning resolution of this system depends mainly from the encoder resolution.

6166-54, Session 12

Power management of actuator/sensor groups for the intelligent control of a flexible structure subject to spatiotemporally varying disturbances

M. A. Demetriou, R. Potami, Worcester Polytechnic Institute

The problem of actuator and sensor placement in a flexible plate is revisited within the context of an intelligent control scheme. Instead of considering individual actuators and sensors, we consider groups of actuators and sensors that have the same capacity to address specific modes. The placement optimization procedure chooses actuators and sensors within a given group so that collectively can address a range of frequencies. Incorporated into the control scheme is the ability to select a given group that can best address spatiotemporally varying disturbances in which the spatial distribution of disturbances changes with time. For the numerical studies on a thin aluminum plate, clamped on all sides and employing piezoceramic patches as collocated actuators/sensors, we consider four groups of PZT actuators/sensors wherein each actuator in each group is designed to have a high level of modal controllability with respect to a given modal shape. Incorporated into the above optimization is the influence of each PZT on the plate's modal shapes. The intelligent control then provides the switching scheme in which, at a given time instance, only one of the four groups is active with the remaining three being kept dormant in order to reduce power consumption.

6166-55, Session 12

Model of an active eddy current vibration controller system

H. A. Sodano, Michigan Technological Univ.

There exist many methods of adding damping to a vibrating structure; however, very few can function without ever coming into contact with the structure. One such method is eddy current damping. This magnetic damping scheme functions through the eddy currents that are generated in a conductive material when it is subjected to a time changing magnetic field. Due to the circulation of these currents a magnetic field is generated that interacts with the applied field resulting in a force. In this manuscript, an active damper will be theoretically developed that functions by actively modifying the current flowing in a coil, thus generating a time varying magnetic field. By actively controlling the strength of the field around the conductor, the eddy currents induced and the resulting damping force can be controlled. The actuation method is easy to incorporate into the system and allows significant forces to be applied without every coming into contact with the structure. This allows vibration control to be applied without inducing the mass loading or added stiffness that are downfalls of other methods. This manuscript will provide a theoretical derivation of the equations defining the electric fields generated and the dynamic forces induced in the structure. This derivation will show that when eddy current are generated due to a variation in the strength of the magnetic source the resulting force occurs at twice the frequency of the applied current. This frequency doubling effect will be experimentally verified. Furthermore, a feedback controller will be designed to account for the frequency doubling effect and simulated to show the significant vibration suppression the can be achieved with this technique.

6166-56, Session 12

Mover device driven by hydrogen storage alloy thin film operated by electric current

T. Ogasawara, H. Uchida, Y. Nishi, Tokai Univ. (Japan)

Using extremely large volume expansion induced by hydrogenation we have developed the mover device operated by electric current.

Hydrogen storage alloy(HSA), such as LaNi5 indicates as much as 25% of volume change in the course of H2 absorption and desorption. We examined to apply this phenomenon to a mechanical mover device as a driving force controlled by the amount of hydrogen in the alloy. In this study an unimorph structural mover device was tested using HSA thin film deposited on an inert substrate.

We confirmed displacements generating drastically large stresses by applying H2 gas. While the amount of hydrogen in the alloy is a function of H2 pressure and temperature, we also tried to control the hydrogen amount in the HSA by electric current directly applied in the film in a closed system.

We report discussions on results with precise relationship between current and displacement under different temperatures.

Displacement can be achieved by the temperature change caused by the electric current placed under ambient H2 pressure, therefore, the results indicate the possibility of mover devices with simple structure similar to an artificial muscle controlled by electric current.

6166-57, Session 13

Control of enclosed sound fields using shunted piezoelectric circuits

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In this article, the modeling and control of enclosed sound fields using shunted piezoelectric circuits is investigated. A spherical wave, which is generated by a noise source located in the near field, is transmitted into a rectangular enclosure through a flexible panel. Piezoelectric patches, which are bonded symmetrically to the top and bottom surfaces of the panel, are shunted through electric shunt circuits and are used as energy dissipaters. Microphone sensors are used inside and outside the enclosure for acoustic pressure measurements and polymer based piezo (PVDF) film sensors are bonded to the top surface of the plate for vibration measurements. The shunted circuits are developed such that the acoustical effects of the first three dominant vibration modes can be attenuated, and this feature makes it appealing for noise control schemes for multiple tones. The numerical predictions of the noise attenuation levels are found to be in good agreement with the corresponding experimental measurements.

6166-58, Session 13

Active control of dispersive waves: coupling finite-dimensional control system using isospectra

D. Roy Mahapatra, Wilfrid Laurier Univ. (Canada); B. Balachandran, Univ. of Maryland/College Park

High dimensionality in the control of waves or more precisely the control of vibro-acoustic disturbances is one of the most demanding aspects in designing smart structures. Although, various problems in the context of linear control have been addressed mathematically in literature, they are not well realized in high-dimensional active control system. Among the main reasons behind this are (1) the lack of physical means to realize those well-defined mathematical properties, estimates and their bounds and (2) the use of the standard notion of state-space observability-controllability as a min-max problem rather than taking advantage of the spectral properties of the coupled structure-control system under consideration. A new design methodology for active control of linear dispersive waves in elastic structure is reported in this paper. The concept is based on evaluating a hypothetical constitutive model and its spectral characteristics that follows certain desired dissipative behaviour if realizable in an infinite-dimensional system (e.g. beam, plates etc.). This spectral characteristics is then used as a differential inclusion in a finite-dimensional feedback control system (sensors and actuators in closed-loop) which is integrated with the elastic host structure. It is then discussed how this idea can be extended to a smaller length-scale involving array of MEMS transducers inherent to material microstructure. The proposed methodology is applicable to problems involving the control of acoustic waves in passive-active material system with complex constitutive behaviour at different length-scales. In the present paper we consider a strain rate type constitutive model which can be correlated to feedback control involving physical phenomena such as piezoelectricity, memory effect, and rheology. Numerical simulation of flexural wave control in beam is carried out. Two-sate feedback sensors (namely a shearing strain sensor and a curvature sensor) and two tunable bending-shear actuators are considered for a structural element with given length-scale. The resulting coupled structure-control system are parameterized in the solution space of the design variables, namely the strain-rate coefficient, the wavelength(s) to be controlled and the location of the sensors. The characteristics of the controller transfer functions and their pole-placement problem are studied. Various practical engineering issues related to the usual notion of asymptotic stability and robustness for the proposed concept are addressed.

6166-59, Session 13

The noise reduction using smart panel with shunt circuit

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If we consider the transmission of sound through a partition, we can actually measure the sound energy on both the source side and the receiving side to determine exactly what fraction of the sound is transmitted through. The term Transmission Loss (TL), or more commonly Sound Reduction Index (SRI) are used to describe the reduction in sound level resulting from transmission through a material. In this paper, a broadband shunt technique for increasing transmission loss will be experimentally investigated. Some new approaches in the modeling of smart panel as well as shunt damping techniques will be discussed.

In the modeling process, the PZT patch bonded on the main structure forming the smart panel, numerical results can be achieved in terms of commercial soft packages such as ANSYS and NASTRAN. Taguchi method will be applied in the optimal design process to obtain the optimal configuration of the smart panel. The impedance model based on the measured electrical impedance will be applied by adopting Van Dyke's equivalent circuit and electrical impedance is simulated with the commercial soft packages in order to predict the performance of piezoelectric shunt damping. The simple shunt circuit is used to damp the vibration of the smart panel because of its low cost and simplicity. The synthetic inductor substitutes the coil inductor and makes the circuit more flexible and tuning easily for the optimal control when it is used practically. To verify the transmitted noise reduction using shunt circuit, reverberation chamber and anechoic chamber will be applied based on the standard SAE J1400 and different models of transmission loss will be measured based on the octave analysis to certify the performance of smart panel. The single-mode shunt damping will demonstrate a remarkable noise reduction at specific resonance.

6166-60, Session 13

Active acoustical impedance using distributed electrodynamical transducters

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New miniaturization and integration capabilities available from the emerging MEMS technology will allow silicon-based artificial skins involving thousands of elementary actuators to be developed on the near future. SMART structures combining large arrays of elementary motion pixels coated with macroscopic components are thus being studied so that fundamental properties such as shape, stiffness, color, and even reflectivity of light and sound could be dynamically adjusted. This paper investigates acoustical impedance capabilities of a set of distributed transducers connected with suitable controlling laws. The paper aims at showing in a first part how a well controlled semi-distributed active skins can modified substantially transmissibility or reflexibility of the corresponding homogenous wall. In a second part efficiency of such device is compared with those obtained by classical X-filtered Feedforward strategy.

Basically, we search to design an integrated electro-mechanical system which presents a global behavior with appropriate acoustical characteristics. This problem is intrinsically connected with the control of multiphysical system based on PDE and with the notion of multi-scaled physic when we use MEMS devices.

The used method to design a dedicated control strategy connects the technological or physical aims of the desired system with the design of a collocated or quasi-collocated active behavior law. To explain this notion, let us consider a simple semi-infinite 2D fluid-structure interface covered with distributed transducers which can be connected by suitable electronics circuits. The optimization problem is also to induce in this interface some new acoustical properties such as total absorption or reflexion by designing a dedicated distributed discreet control operator.

By using specific techniques based on partial derivative equation control theory, we have first build a simple boundary control equation able to annihilate wave reflexion. The obtained control strategies can also be discretized to be implemented like a zero or first order spatial operator. Thus, we can use quasi-collocated transducers and their well-known poles-zeros interlacing property to guarantee robust stability. Furthermore this decentralized approach decreases the difficulties in implementing it on a large discreet system. Indeed, each transducer does not need to be addressed by a centralized computer but can simply be used by some decentralized distributed controllers. One can imagine the decrease of CPU times for MIMO systems.

Finally numerical and experimental results underline the capabilities of such a methods. Comparisons with classical x-filtered LMS techniques are also present to underline the efficiency of the proposed strategy.

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6167-01, Session 1

Differential phase tracking applied to Bragg gratings in multicore fiber for high-accuracy curvature measurement

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Optical fiber Bragg grating (FBG) strain gauges have been used for structural monitoring in civil, marine, and aerospace applications. Structural deformation and bending is of interest in many applications and is often inferred from the measured strain at a number of points in the structure. The accuracy of the deformation or bend measurement is dependent on the strain transfer between the structure and FBG strain gauges; the precise knowledge of the gauge locations and the algorithm used. A direct measurement of curvature is desirable for certain applications and curvature sensors using FBG strain gauges have been reported by measuring differential strain in a structure.

Temperature-insensitive curvature measurement has been simply demonstrated by applying FBG strain gauges to opposite sides of a cantilever beam. However this demonstration is sensitive to temperature gradients across the cantilever beam. A more robust curvature sensor can be fabricated by writing FBG strain gauges in to three cores of a multicore fiber (MCF). The MCF accurately defines the core separation and promotes good thermal stability between cores as a result of the small core separation. Direct two-axis bend measurement can be made by differential strain sensing between the cores of the MCF. However, the small core separation requires improved strain measurement.

In this paper we report the application of a practical interferometric interrogation technique for direct differential strain sensing in separate cores of a MCF for high resolution quasi-static and dynamic curvature measurements. The MCF has an outside diameter of 125microns, which is the same as standard singlemode fiber, but has four singlemode cores orientated in a square with a pitch of 50microns. FBGs are written in to the separate cores of the MCF and a fan-out is constructed to interrogate each core independently. High resolution quasi-static measurements are achieved by measuring the differential phase between the FBG sensors, which compensates for the random drift of the interrogating interferometer. A DC curvature accuracy of (radius of curvature = 333m), and an AC curvature resolution of (radius of curvature 8.33km) are reported. This interrogation technique can be readily combined with wavelength- and time-division multiplexing to allow the potential to interrogate up to 500 FBG curvature sensors in a single fiber.

6167-02, Session 1

Packaging of surface relief fiber Bragg gratings for use as strain sensors at high-temperature

R. H. Selfridge, S. M. Schultz, T. L. Lowder, Brigham Young Univ.; A. Méndez, MCH Engineering LLC; V. P. Wnuk, Hitec Products Inc.; S. Ferguson, T. W. Graver, Micron Optics, Inc.

Optical fiber Bragg grating sensors have seen an increased acceptance as well as a widespread use for structural sensing and monitoring in civil engineering, aerospace, marine, oil & gas, composites and smart structure applications. However, one of the drawbacks of standard FBG sensors is that their spectral response decays when exposed to elevated temperatures (\>200°C). Removing this limitation is particularly necessary and attractive in harsh environment and high temperature applications-such as automotive, industrial process control and aerospace-where conventional foil strain gauges cannot operate. In addition, another area in need of further development and commercial maturity is that of sensor packaging.

Several means have been developed to improve the thermal stability of FBGs such as doping fibers with tin, using N-doped silica fibers, single-pulse laser writing or relying on chemically-modified gratings via temperature annealing. In this paper, by contrast, we report on an alternative type of high-temperature resistant fiber grating based on the chemical etching of a grating structure into the surface of a D-shaped fiber. Samples of etched FBGs were surface mounted onto support substrates and packaged using a special, glass-filled high-temperature, epoxy compound. The etched grating fabrication and its packaging procedure will be discussed along with experimental results on the sensor's strain and temperature response at elevated temperatures and under extreme RH conditions.

6167-03, Session 1

Development of small-diameter optical fiber sensors and high-speed optical wavelength interrogator for damage detection in composite materials

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We study a sensing system for health monitoring of aircraft structure made of composite materials. This sensing system is composed of fiber Bragg grating (FBG) sensor and a piezoelectric transducer (PZT). The FBG sensors receive elastic wave of several hundred kHz generated by the PZT.

For this sensing system, we have developed the FBG sensors using the polyimide-coated small-diameter optical fiber with cladding diameter of 40 micrometer and core-cladding relative index difference of 0.65 %, which can be embedded in composite materials without inducing any structual defects. However, the small-diameter optical fiber is too thin cladding diameter. The transmission loss of the small-diameter optical fiber increase more than in case of normal single mode optical fiber under embedded conditions because of macro bending loss and micro bending loss. So, we developed a new small-diameter optical fiber with cladding diameter of 40 micrometer and core-cladding relative index difference of 1.0% and 1.8% in order to suppress loss increase due to bending or strain. And, the small-diameter optical fiber is too fragile and hard to handle. In practical use, the small-diameter fiber needs to be joined to a normal optical fiber with a 125-micrometer cladding diameter. So, we developed a small-diameter optical fiber modules which can connect the normal optical fiber.

For high-frequency vibration monitoring, we have developed a high-speed optical wavelength interrogator, which can detect the high-frequency vibration of the FBG sensors. In this interrogator, we used an arrayed waveguide grating (AWG) as an optical filter which converts wavelength shift of the reflecred light from the FBG into the output optical power change. This system is suiatable for high-speed wavelength detection because there is no mechanical moving part.

In this paper, we presents the estimation result of small-diameter optical fiber with high relative index difference using high-speed optical wavelength interrogator and the joining techniques promoting the usage of the small-diameter optical fiber for practical heath monitoring systems.

6167-04, Session 1

Characterization of a fiber optic shape and position sensor

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We report the results of a study of the performance characteristics of a fiber-optic shape and position sensor. Strain measurements from distributed fiber Bragg gratings in a multi-core optical fiber multiplexed via the frequency domain reflectometry technique are used to deduce the shape of the optical fiber. We have measured a range of two and three dimensional shapes using a multi-core fiber with a sensor spacing of 1.0 cm and a gage length of 0.5 cm and have reported the accuracy and precision of these measurements. A discussion of error sources is also included.

6167-05, Session 2

A self-interfering fiber optic acoustic emission sensor system with fiber optic Bragg grating

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This paper describes a self-interfere optic fiber sensor (SOFS) system which can be used to detect acoustic emission companying the damage in structures. The system consists of laser diode(LD), fiber optic Bragg grating (FBG) filter, optical fiber lead line ,sensing arm and reference arm , photo diode (P/D) , voltage amplifier and data analyzer system. The fiber optic Bragg grating filter is used to reflect the certain wavelength light produced by LD and thus get the narrow bandwidth light which is led into the sensor arm and reference arm. For the light reflected from FBG described in this paper, the coherence length light is about 18mm, it is very easy to keep the light reflected from the end of the two arms as soon as keep the optical path difference between the two arms less than 18mm, no additional online phase adjust device is needed on reference arm, the sensor system is very

simple.

When the strain wave induced by the acoustic signal acts on the sensing arm, the fiber optic arm's physical length and reflective index will change slightly and thus induce the phase shift in the interferometer system. The phase shift can be detected easily by transferring the optical signal into the electrical signal through the P/D amplifier.

The sensor system is tested by a serial of experiments. The sensitive of the system is evaluated by the pencil lead breaking test. To test the robust of the system, the output voltage in waiting state is monitored in 48 hours and it is found that the fluctuation level is small enough compared to the acoustic emission response signal. The system has no response delay for the acoustic emission signal and can identify the different signals act on the sensing arm in a short time. In this system, the two arms can be used as the sensing arm and this two arms act as the reference arm each other. When the two arms are under the same temperature field, the influence of the temperature can be eliminated automatically.

The sensing arms are embedded into fiber reinforced samples which are loaded to break point. It is verified by the experiments that the sensing system present here is efficient to detect the breakage of the fiber in the FRP material.

6167-06, Session 2

High-spatial resolution measurements of transverse stress in a fiber Bragg grating using four-state analysis, low-coherence interferometry, and layer-peeling

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Fiber Bragg grating (FBG) sensors have been shown to be a good means of non-destructive monitoring of the stress and/or strain of the materials in which they are embedded. Many FBG transverse stress/strain measurement systems can only resolve a single stress and/or strain value for the entire length of the FBG and often require the use of polarization-maintaining fiber. We demonstrate a new method for measuring the two components of transverse stress with high spatial resolution in a distributed FBG sensor. A directional compressive load is applied by placing weights on top of the FBG, creating a transverse stress in the core of the FBG. Small metallic strips are placed under the FBG to create a localized stress in the FBG. The index of refraction as a function of position in the FBG is measured using a low-coherence Michelson interferometer and a layer-peeling algorithm. With this method we are able to measure changes in the refractive index with resolution better than 5*10-6, limited by the signal-to-noise of the measurement system, with a spatial resolution of 16 μm, which is determined by the spectral bandwidth of the low-coherence source. To determine transverse stress/strain, we repeat the measurement for four different polarization states. A four-state analysis is then used to determine the birefringence as a function of position in the grating. This measurement assumes that the applied transverse load is much larger than any other birefringence in the grating, so that the principal axes do not change with position in the grating. This measurement offers the advantage that it can be implemented with a simple layer-peeling algorithm, and it does not require the use of expensive polarization maintaining fiber. Measurements of the externally induced birefringence agree well with values predicted using the stress-optic properties and the geometry of the fiber.

6167-07, Session 2

Multiplexed adaptive two-wave mixing wavelength demodulation of fiber Bragg grating sensor for monitoring both dynamic and quasi-static strains

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A multiplexed 16-channel version of two-wave mixing (TWM) wavelength demodulator using InP:Fe photorefractive crystal (PRC) in the C-band (1530-1570nm) is demonstrated. The system can be used as a wavelength demodulator for use with Fiber Bragg Grating (FBG) sensors to monitor both dynamic strains and quasi-static strains. In this configuration, the FBG is illuminated with a broadband source, and any strain in the FBG is encoded as a wavelength shift of the light reflected by the FBG. The reflected light from the FBG is spilt into two unbalanced paths and both beams (pump and signal) mix in the PRC. Any wavelength shift of the reflected light results in an equivalent phase shift between the pump and signal beams as they travel unbalanced path lengths. Since TWM is an adaptive process, the two interfering beams are naturally in quadrature and remain in quadrature even in the presence of large quasi-static strains. Quasi-static strains can be obtained by monitoring the spectrum shift of the transmitted pump beam. Finally, the TWM wavelength demodulation system is used to demonstrate the impact monitoring on a real composite panel.

6167-08, Session 2

Unique characteristics of surface relief fiber Bragg gratings and their application to multiaxis sensing

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In submitting this extended abstract I am requesting consideration for the 2006 SPIE/ASME Best Student Paper Presentation Contest.

Fiber Bragg gratings (FBGs) have become an imperative device in optical communication and optical sensing technology. Because they are a not a bulk optic component they exhibit low insertion loss and are easily integrated into contemporary systems. Existing FBGs are fabricated such that a periodic modulation in the index of refraction is photoinduced into the core of the fiber. This periodic modulation reflects a narrow band of wavelengths centered on the Bragg wavelength while transmitting all other wavelengths.

As an alternative method to creating a Bragg grating, we etch the grating into the flat surface of an elliptical-core D-fiber. The flat surface of the D-fiber is etched close to the core so that the grating can influence the guided light. The gratings are about 1.5 cm long, 0.4 microns above the core and have a peak-to-trough distance of about 80 nm. These surface relief fiber Bragg gratings (SR-FBGs) demonstrate many unique characteristics that are not apparent in standard FBGs.

In this paper we explore these characteristics and how they can be exploited for use in multi-axis sensing applications. Specifically, we use the grating and the fact that D-fiber has high birefringence to create a multi-axis strain sensor that can be used to simultaneously monitor both longitudinal and transverse strain. In addition, because the grating is on the surface of the fiber, the gratings tilt angle can be changed by simply bending the fiber. This allows us to also use SR-FBGs as a multi-axis bend sensor. Lastly, SR-FBGs demonstrate a strong polarization dependence that is not experienced in other FBGs.

We create a multi-axis strain sensor by monitoring both the Bragg wavelength and the output power of the transmitted light. Longitudinal strain (strain along the fiber axis) is detected by tracking the Bragg wavelength. Increasing strain causes the period of the grating and the effective index of the fundamental mode to change. These changes cause the Bragg wavelength to shift and this shift is correlated to longitudinal strain. Experimentally gathered data shows that the shift in wavelength versus the applied strain is linear. The strain sensitivity of our SR-FBGs is 1.2 pm/microstrain.

Transverse strain (strain orthogonal to the fiber axis) is detected by monitoring the output power of transmitted light. Increasing strain alters the cross sectional dimensions of the fiber and thus changes the effective indices of the two orthogonal polarizations of the fundamental mode, but they change by different amounts. This causes the birefringence to change as more strain is applied to the fiber. By placing a polarizer at the input of the fiber and an analyzer at the output, the change in birefringence can be measured by monitoring the output power. Using Young's modulus this data is then correlated to find the transverse strain.

SR-FBGs can also be implemented as multi-axis bend sensors. As the fiber is bent up and down the grating period increases or decreases which causes the Bragg wavelength to shift. As the grating is bent side to side, the grating experiences a tilt. Other researchers have shown that this tilt reduces the efficiency of the grating and thus reduces how much light is reflected at the Bragg wavelength [1]. By monitoring the shift of the Bragg wavelength and also its efficiency, a multi-axis bend sensor can be attained.

Lastly, we have found that the y-polarized mode (light polarized along the minor axis of the core) has less field concentrated in the area of the grating, and therefore reflects less strongly than the x-polarized mode (light polarized along the major axis of the core). The y-polarized mode is much less efficient because the glass-air interface causes a large index modulation ($\Delta n \sim 0.45$) and a small field overlap (the amount of modal field that falls in the physical area where the index modulation occurs). Simulations show that a notch due to the y-polarized mode is approximately 20 dB less deep then a notch due to the x-polarized mode. Decreasing the index modulation with the use of index matching oils increases the field overlap and the overall efficiency of the y-polarized mode. This strong polarization dependence allows us to use SR-FBGs as wavelength selective polarizers by filtering out the y-polarization at specific wavelengths.

In conclusion, we have shown that there are many unique characteristics of SR-FBGs. These unique characteristics allow SR-FBGs to be used in a number of multi-axis sensing applications. They exhibit high birefringence, can easily be tilted, and demonstrate strong polarization dependence. Therefore, SR-FBGs provide a viable alternative to existing multi-axis sensors.

References

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6167-10, Session 3

Fiber grating sensors for structural health monitoring of aerospace structures

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Fiber optic grating sensors can be used to support a wide variety of measurements that are necessary for structural health monitoring of aerospace structures. This includes their usage to measure structural integrity of composites using "strain imaging", monitoring of adhesive bond lines, measurement of corrosion and moisture in key areas, and overall deformation measurements. This paper will provide an overview of fiber grating sensor technology that is of particular interest in aerospace applications and review how it is being applied.

6167-11, Session 3

An application test using Brillouin optical frequency domain analysis method for aircraft structural health monitoring

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The necessity for airplane structural health monitoring technology has been increasing, because of improvement of reliability and maintenance cost reduction. Optical fiber sensing system is an attractive scheme for airplane structural health monitoring. There are great hopes for applying the system to airplane structural health monitoring because of the light weight, non-electromagnetic interference, durability and capability of sensors to be embedded to composite structures. Especially the distributed optical fiber sensor fits the health monitoring for large-sized structures. However, the distributed optical fiber measurement system using the pulse light represented by the Brillouin optical time domain reflectometer has low spatial resolution and long measurement interval. These performances have been the obstacle of application to airplane structure health monitoring system. Then, the authors have proposed the Brillouin optical frequency modulation method for improvement of the spatial resolution.

In this work, we developed the distribution measurement and the high-speed measurement of arbitrary points technology using Brillouin optical frequency domain analysis method. In this development, we achieved 50mm of spatial resolution and 1Hz of measurement responses of arbitrary points. Moreover, we considered substructure test and flight demonstration test to verity the validity of BOFDA sensing system. From these results, it was confirmed that BOFDA system has potential to be applied to an airplane structure health monitoring system.

6167-12, Session 3

Structural health monitoring of composite T-joints for assessing the integrity of damage zones

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This paper uses one category of Structural Health Monitoring (SHM) which uses strain variation across a structure as the key to damage detection. The structure used in this study is Glass Fibre Reinforced Plastic (GFRP). GFRP's are used often these days in military warfare because of its distinct advantages namely; high strength to weight ratio, high stiffness, ability to form complex shape, and also for stealth. However, GFRP's are also prone to delaminations and matrix cracking, which could lead to a catastrophical failure of the structure if gone undetected.

This paper discusses a technique developed to sense the presence of damage, determine the location and also determine the extent of damage. Finite Element Models (FEM)of T-joints found in most ship structures are created using MSC/Patran. This FEM is modelled with delaminations at various locations across the bond-line of the structure. And the resulting strain variation across the surface of the structure is observed. A prototype of the model was then manufactured at RMIT University and it was tested to corroborate the FEM Model. Signal processing techniques where then used to determine the presence, location and size of the crack, from the strain variation pattern of the structure. The signal processing techniques used included both Artificial Neural Networks and Statistical Techniques. The signal processing techniques used have been shown to predict the location of damage for a number of simulated cases. The effect of pre-processing the strain distribution using the Damage Relativity Analysis Technique (DRAT) has also been discussed.

Future work proposed includes the extension of this technique to predict the remaining life span of the structure. The use of vibration response signals instead of the strain signature is also proposed.

6167-13, Session 3

Safety and security monitoring of dams using nano-micromachined-based surface acoustic wave (SAW) sensors

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Concerns about the safety of concrete dams have increased during recent years, partly because of the expanding number of "at-risk" citizens located downstream of major dams. These dams have long-term damage and inadequate seismic design. The damage could be detected with intense inspection of the bridges and can then be repaired or even replaced. In the US alone, there are more than 78,000 dams that pose a safety hazard to their environments. More than 2,900 nonfederal dams in the US were declared unsafe. Today, the replacement and repair of bridges cost the United States billions of dollars each year. The long-term deterioration of these mass structures are manifested in the form of cracks due to freeze/thaw cycles, oxidation, decay, thermal stresses and ASR. These micro cracks will eventually become wider and can develop into holes or delamination, thus presenting a safety problem for the dam. A large number of dams have been damaged by ASR where high moisture levels are present in concrete which assist in producing ASR gel. Swelling of this ASR gel can lead to cracking and overall expansion of the affected structure. As a result of this damage, the structure loses strength, particularly in flexure, stiffness and impermeability. Serious threats to concrete dams often involve cracks in the dam's abutments and foundation. These cracks are usually in remote locations and are invisible to inspection. Since the assessment of the dam integrity and safety is being done via onsite visual inspection, these invisible and remote cracks can be undetected until they become severe. This could lead to a catastrophic failure. Reliable techniques for continuous monitoring of certain key parameters affecting the dam's integrity are currently nonexistent. This is due to the lack of sensing technology capable of functioning in a hostile milieu such as low temperature, high moisture levels, and other environmental variations. The objective of this paper is to investigate the possibility of incorporating MEMS based SAW sensors to detect moisture (H2O), Ph, CL-, and CO2 located internally in the concrete of dams; thus preventing the decay of internal elements which may lead to catastrophic failure. These sensors are to be passive and should not require much power for performance. They also are going to be low cost and wireless devices. Success in this project will ensure the safety of inhabitants who reside in close proximity to these dams. Preliminary results obtained from sensor simulation and experiment will be presented.

6167-14, Session 3

Smart FBG-based FRP anchor

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FRP has become the popular material to alternate steel in civil engineering under the harsh corrosion environment. But due to its low shear strength ability, the anchor for FRP is most important for its practical application. However, the condition at the surface between FRP and anchor is not fully understood due to that there is no proper sensor to monitor the inner strain in the anchor by traditional method. In this paper, a new smart FBG-based FRP anchor is brought forward, and the inner strain distribution of a kind of FRP anchor has been monitored using FRP-OFBG sensors, a smart FBG-embedded FRP rebar, which is pre-embedded in the FRP rod and cast in the anchor. The distribution of bonding shearing stress on the surface of FRP rod along the anchor is obtained. This method can supply important information to FRP anchor design and can also monitor the anchorage system, which is useful for the application of FRP in civil engineering. The studies result show that the smart FBG-based FRP anchor can give direct information of the load and damage of the FRP anchor, which is proper for practical applications.

6167-15, Session 3

The strain and temperature measurements of RC building based an embedded FBG sensor system

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Proper monitoring of building performance will be useful to optimize maintenance scheduling and to minimize maintenance costs. The benefits of the information obtained by monitoring during each period of the structure life are apparent will help to improve and enlarges the knowledge concerning structural behavior and makes an accurate calibration of numerical models possible and permanent monitoring can give early indication of structural malfunctioning. In this way, safety measures can be considered in time, and intervention on the structure can be performed immediately and with minimal economical losses. This paper discusses the monitoring of the temperature change and strain changes of a 5-story rein-

force concrete building by an optical fiber Bragg grating sensor system in building construction course. Based on the project result the packaged FBG used in measurement is feasible and superior to strain gauge and evaluate the reliability of FBG sensor system for a long period. This project also provides some useful advice for structure health monitoring.

6167-16, Session 3

Sensitivity analysis of dynamic properties of shear buildings in damage detection

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Sensitivity analysis of dynamic properties of shear buildings in damage detection: The objective of this paper is to study the change law of the sensitivity coefficients of dynamic properties of shear buildings, and make dynamic properties to be effectively used in damage detection. Firstly, the absolute and relative sensitivity coefficient expressions are derived from structural vibration equation. Then, the sensitivity analysis is applied to a 10-story shear building. All of the sensitivity analyses show higher modes are more sensitive than lower modes to damage. Through frequency sensitivity analysis, it is helpful to choose a few lower frequencies as indicator of damage. By means of mode shape sensitivity analysis and the slope of mode shape sensitivity analysis, it can be found the slopes of mode shapes are more sensitive than mode shapes to damage. Damage always results in the increase of the slope of first mode shape corresponding to damage location, and it is very useful for damage localization.

6167-17, Session 4

Industrial design of instrumented PRC elements for the condition monitoring of civil infrastructure

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Recognizing the growing importance of new technologies in the life-cycle management of civil infrastructures, the University of Trento is promoting a research effort aimed at developing a novel construction system that will allow real-time condition monitoring of bridge structures. The general concept is to build new bridges using smart structural elements, i.e. precast RC elements embedding a sensing system and capable of self-diagnosis. Sensors are not just applied to the member, but are conceived as an integral part of the prefabricated element, influencing its design criteria, performance and detailing Depending on the type of instrument used, a smart element will potentially be capable of self-detecting point to point physical quantities such as: strain and stress distribution; vibration response; cracking location and extension; temperature; moisture; pH; chloride concentration. An Internet-based Bridge Management System will be able to interpret these quantities in terms of condition state and reliability, and will make these available to those concerned. As sensors are activated, all those involved in the production/management process can connect via the Internet, at any time and from any location worldwide, and directly check the actual condition of the element, during production, transportation, construction and operation.

A first step of the research was accomplished in 2004 with the construction and testing of reduced-scale prototypes of smart elements. The objective was to develop simplified elements, suitable for extensive laboratory testing, yet comprising all the features enabling them to reproduce the behavior of the full-scale structure. While the scope of the first phase of the project was to validate the performance of fiber optics based sensing systems applied to RC elements, the second phase aims at demonstrating the industrial feasibility of the series production of prefabricated elements embedding FOS technology as well as their in-field reliability. In detail, the program includes the production of two 21m-long prestressed RC box girder elements. One of the two elements will be employed in the construction of a single span road bridge, while the other will be extensively tested in the laboratory, in order to record and identify the response signature associated with recurrent deterioration scenarios, including cracking, concrete cover spalling and partial corrosion of the reinforcement.

The general paradigm of the design is to conceive the sensing system in two separate parts, embeddable and external. The embeddable part is to be permanently installed in the element, and therefore must have high durability and robustness. The embeddable sensing system is prepared in the form of linear subassemblies referred to as smart bars. In a smart bar, all optical sensors and wires are mounted on a modular aluminum support specifically designed for the purpose. Optical signals are carried along the smart bar and collected at the element edges. The production process in the prefabrication plant starts with steel reinforcement pretensioning, and the smart bars are easily arranged in the framework along with the non-tensioned reinforcement, before pouring the concrete. The external part of the sensing system includes the interrogation units and the telecommunication system. These parts are conveniently located at the edges of the element at an easily accessible position. Once the bridge is in operation the external sensing system can be replaced during routine maintenance work or as necessary in the case of malfunction, or for technology upgrade.

6167-18, Session 4

Self-organizing wireless sensor networks for structural health monitoring

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Structural health monitoring represents a class of sensor network application with enormous benefits. By embedding sensors on civil infrastructures, various failures such as excessive cracking, overstress, anchorage pullout, delamination, and corrosion can be detected in real-time at the incipient stages. The integration of local processing and storage allow sensor nodes to perform complex feature extraction and triggering functions, and data compression. In order to successfully detect these failures, the embedded sensor nodes must form a self organizing wireless network that can collectively send data to a base station for decision making. In this paper an effective way of self organizing the sensor nodes for transmission of data is investigated.

A novel self organizing method to cluster sensor nodes is presented for structural monitoring applications by clustering the nodes around a region in the network only when a failure event is detected. In general sensor nodes have power, memory, and bandwidth constraints. In order to conserve the energy, normally the nodes in the sensor network are in idle or sleep mode. If nodes around a failure region start sensing incipient failures, they form into sub-networks that consist of nodes that have signal strength greater than a predefined threshold value. Using the nodes in the sub networks, initial cluster heads were selected and clusters are formed based on the received signal strength due to a failure. Once clusters were formed, the node with the maximum available energy in each cluster will be selected as the new cluster head. These cluster heads in turn form a multihop network to transmit the aggregated data from each cluster to a base station. This process of self-organization is repeated as the event propagates. The performance of the proposed scheme was analyzed and metrics such as energy, delay, and throughput were utilized to compare available methods to the proposed one. The proposed method is applied to a simulated example and the results demonstrate that less energy is consumed and the end to end time delay is reduced when compared with the existing LEACH (Low Energy Adaptive Clustering Hierarchy) algorithm. The proposed method is scalable as the new nodes does not increase the overall amount of energy used for self organization since the clustering is done around the failure region in contrast with other methods.

6167-20, Session 5

Long-term stability of a new EFPI stress monitoring sonde installed in a brown coal mine in Poland

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In cooperation with BAM the German federal institute of material testing, Mining Construction Research and Development Centre BUDOKOP from Myslowice Poland a new measuring system EFPI (Extrinsisch Fabry Pérot Interferometer) with zero point measurement was developed and for a first important installation used to get site experiences.

The installed stress monitoring system consist of 3 single pressure sensors orientated in 3 directions to monitor 2 dimensional main stress in rock in direction and value.

For long term measurements and interpretation drift effects have to be avoided or / and controlled.

A zero point measurement and control is done with every measurement and is approving the long term results.

A new quality of result and interpretation is reached and possible as not only sensibility is increased, we have now approved results.

Experiences and first results will be reported for discussion.

6167-21, Session 5

Real-time fiber optic sensor demodulation schemes based on phase-shifting interferometry with error compensations

Z. Chen, M. Yu, Univ. of Maryland/College Park

In this paper, the recently developed high-speed, real-time fiber optic sensor demodulation techniques based on low coherence interferometry and phase-shift-

ing interferometry are presented. The demodulation schemes are applied to a pressure sensor system that consists of a Fabry-Perot sensing interferometer and an integrated optical circuit phase modulator as a reference interferometer. Various conventional phase-stepping algorithms and novel algorithms with error compensations are investigated as to how to reduce the errors in the demodulated phase signals. The errors introduced in the phase demodulation include several sources: random intensity measurement errors, errors related with interference fringe visibilities, phase shifting errors, and errors associated with phase modulation frequency. Both theoretical and numerical analyses are conducted to compare the performances of the demodulation schemes based on different phase-shifting algorithms. We also provide the experimental data from high-frequency acoustic measurements and static force measurements to look into the robustness of these phase-shifting algorithms to various error sources. These analysis and experimental results will give guidelines for choosing appropriate phase-stepping algorithms in sensor demodulation schemes and improving the sensor accuracy and bandwidth.

6167-22, Session 5

Inversion technique for an all-optical inspection of materials' elastic properties

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Helped by the modern advances in computer power and Signal Processing techniques, ultrasonic guided waves inspection has emerged recently as a promising Non-destructive Testing tool for Structural Health Monitoring.

Ultrasonic guided waves inspection is able to provide information not only of the presence and location of surface and internal damages in plate-like structures, but also it can provide information about the severity of the damage. In addition to its lightweight, inexpensive and portability capabilities, ultrasonic guided waves inspection allows structural integration and non-contact and remote monitoring.

In this paper we present an inversion technique, applied to a complete non-contact, all-optical inspection tool, for the extraction of the most important mechanical characteristics of plate-like structural materials (effective stiffness, Poisson ratio and plate's thickness).

A short pulse high power laser is used for the optical generation of broadband ultrasonic guided waves, which in our plate-like application corresponds to Lamb waves. In the reception stage we use a Michelson modified surface displacement optical fibre interferometer, which provides very good sensitivity for the remote detection of the ultrasonic waves.

The advantage of using Lamb waves for the inspection of the materials is that they interact with the structure's entire thickness propagating longer distances than other acoustic waves. They also provide a strip area inspection allowing fast coverage of large structures in opposition to other point scanning ultrasonic inspection techniques such as C-scan.

The Lamb waves propagation characteristics are very much affected by the material's elastic properties as well as by its geometrical conditions (e.g. plate thickness). We apply by two different and complementary signal processing techniques over the detected waves time signals in order to display their propagation information in the so-called Lamb waves dispersion curves. A two dimensional Fourier transform gives as the phase velocity dispersion curves with propagation information of the local region where the ultrasonic sources are located. On the other hand a time-frequency analysis gives us the group velocity dispersion curves with information of the global region between the source and the sensor.

By looking into the asymptotic behaviour of the obtained dispersion curves we achieve a first estimation of the dynamic elastic and geometrical properties of the material, based mainly in frequency thickness product information. The obtained elastic properties are later used as initial values in an optimized inversion procedure applied to the Lamb waves' velocity information, for a more accurate and complementary elastic properties estimation.

In the development of the inversion procedure different weighting factors are analyzed, for the minimization of the theoretical and experimental dispersion curves difference. The inversion process is considerably affected by the regions of the dispersion curves to which it is applied. An examination of this effect helps us to choose an adequate region of analysis. Applying this technique to the two different obtained dispersion curves will provide us with local and global elastic properties information of the specimen under test.

A monitoring of the changes in the estimated material properties could be used as an indicator of the presence of structural condition perturbations.

6167-23, Session 5

Sensitivity of an extrinsic Fabry-Perot interferometric sensor with respect to the alignment direction of the sensor for detecting lamb waves

D. H. Kim, Univ. of California/Irvine; Y. Kim, Agency for Defense Development (South Korea); C. Kim, Korea Advanced Institute of Science and Technology (South Korea)

Lamb wave is a good method to detect some imperfections in a thin plate. In order to use this method, a sensor as well as an actuator is needed. Usually, a piezo-ceramic transducer is a good sensor and also a good actuator. Nowadays, fiber optic sensors are good alternative transducers for detecting Lamb wave as well as other ultrasonic waves. However, in the case of the fiber optic sensor, its sensitivity has directivity; that is, the sensitivity is variable according to the alignment direction of the sensor because the sensor dominantly measures the displacement induced by the change of gage length along the parallel direction to the sensor. Thus, considering the change of the sensitivity with respect to the alignment direction of the sensor to an ultrasonic source is essential in order to detect the ultrasonic wave using a fiber optic sensor and to determine the absolute amount of the measured value correctly. In this paper, the directivity of the fiber optic sensor was investigated through both a theoretical analysis and an experimental one. The theoretical analysis showed that the sensitivity was related to the alignment angle of the sensor and to the ratio of the gage length of the sensor and the wavelength of the Lamb wave. In the experimental analysis, an extrinsic Fabry-Perot interferometric sensor was used for detecting the Lamb waves which were excited by a lot of piezo-ceramic transducers. One fiber optic sensor was attached on the center of the aluminum plate; otherwise these piezo-ceramic transducers were attached around the fiber optic sensor according to the alignment direction of the fiber optic sensor. Finally, the theoretical results were verified in the experimental analysis.

6167-24, Session 5

A fiber sensor integrated monitor for embedded instrumentation systems

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In submitting this extended abstract I am requesting consideration for the 2006 SPIE/ASME Best Student Paper Presentation Contest.

Optical fiber sensors are finding increased application as smart sensors because of their relatively high immunity to environmental phenomena and small size. They are finding significant use in embedded nondestructive evaluation for monitoring and analysis of civil, mechanical and aerospace systems. While much research is focused on developing and applying new optical sensing technologies, there is also a great need for better fiber sensor interrogators. The current equipment required for interrogating fiber optic sensors tends to be large, bulky and costly, have high power consumption, and usually performs only the most basic functions. While this may be acceptable for current technologies, the demands of new and more complicated smart sensor technologies will require smaller, faster, and more flexible monitoring systems. Several groups have proposed using either a chirped fiber Bragg grating (FBG) system or an arrayed waveguide grating to demultiplex an optical signal into individual wavelengths in order to monitor an FBG sensor. However, such systems are limited when it comes to denser sensor arrays. In this paper a new fiber sensor integrated monitor (FSIM) to be used in an embedded instrumentation system (EIS) is proposed and its operating features are examined.

The proposed system consists of a super luminescent diode (SLD) as a broadband source, a novel high speed tunable MEMS filter with built in photodetector, and an integrated microprocessor for data aggregation, processing, and transmission. As an example, the system will be calibrated with an array of surface relief fiber Bragg gratings (SR-FBG) for high speed, high temperature monitoring. The entire system was built on a single breadboard less than 50 cm(c)¯ in area. The possibilities for use with other multiplexed FBG and Fabry-Perot (FP) sensors are also explored.

The primary component in the proposed system is the MT-15 Tunable Filter, made by Nortel Networks and obtained through an equipment grant sponsored jointly by the National Science Foundation (NSF) and the Defense Advanced Research Project Agency (DARPA). The MEMS filter consists of a Fabry-Perot etalon featuring a half-symmetrical confocal cavity and is available with an integrated photodetector for enhanced compactness. The MEMS filter has a nominal tuning speed of 10nm/μs, a FWHM of 60 pm, insertion loss <3dB, a 25dB suppression frequency of 100 GHz and low power consumption. The integrated photodetector is a standard photodiode operated under -5V reverse bias with a responsivity of 0.6 A/W.

Filter operation was initially characterized using a traditional interrogation system consisting of an optical spectrum analyzer (OSA), external power supply, and computer for data processing. Tuning is accomplished by applying a positive voltage

to the filter drive pin with respect to the filter case. By ranging the applied voltage from 5-35V the filter can be tuned from approximately 1610nm-1515nm respectively. While the voltage-to-wavelength function is not linear, it is sufficiently smooth. The temperature response of the filter was also characterized in order to address the feasibility of operating without a thermo-electric cooler (TEC), which has high power consumption. Experimental analysis showed that the transmitted peak wavelength of the filter had an approximately linear drift when the tuning voltage was held constant while the temperature varied. Analysis also showed that the FWHM of the peak did not change significantly with temperature. Thus by simply monitoring the temperature of the filter, software can be used to offset any peak drift, avoiding the use of a TEC.

The other major components are the SLD and the microcontroller. The SLD used in analysis had a center wavelength of 1530nm and spectral width of 34nm. By using a lower power SLD the use of a TEC was once again avoided. Similarly, a microcontroller was chosen with sufficiently fast operating speed, low power consumption, and the necessary functionality (A/D conversion, I(c)˜C and serial communication, etc.). For experimental purposes the Microchip(c) PIC16F737 microcontroller was used.

Our FSIM system was initially tested using a tunable laser to simulate a fiber Bragg grating. The laser has a FWHM of around 10pm; most FBG's have a bandwidth of 100-200pm. The data points obtained from the FSIM system were transmitted through a serial cable to an external computer where the plot was produced. The system easily tracked changes in the peak wavelength of the tunable laser.

Using the given setup, an expected resolution of 1pm can be attained with a sampling rate in the kHz, and with further optimization possibly in the MHz. The main limiting factors on operating speed are the digital-to-analog and the analog-to-digital conversion rates. The upper limit on sampling speed is the tuning speed of the filter. Since the system already contains an embedded microprocessor, application-based data processing and aggregation can be performed quickly and efficiently before being transmitted to a central processing unit. Because of this, several such systems can be implemented together without placing high demands on the central processing unit. The result is a high speed, dynamic, application specific system.

A new fiber sensor integrated monitor for embedded instrumentation systems has been proposed. This system includes a fully integrated SLD source, a high speed tunable MEMS filter, and an integrated microprocessor, replacing the traditional bulk ASE source, OSA, and external computer. The system will be evaluated with an array of SR-FBG's for high temperature sensing. This new system has the capability for high speed, dense FBG sensor array demodulation.

6167-25, Session 6

Fiber optic contact sensor for cardiovascular operation

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For many years, exploration and treatment of various organs or vessels has been possible using catheter-based diagnostic and treatment systems. Such catheters are introduced through a vessel leading to the cavity of the organ to be explored. In this manner, the patient avoids the trauma and extended recuperation times typically associated with open surgical procedures. To provide effective diagnosis or therapy, it is frequently necessary to first map the zone to be treated with great precision. Often, the mapping procedure is complicated by difficulties in locating the zones to be treated due to periodic movement of the heart throughout the cardiac cycle.

It therefore would be desirable to provide apparatus and methods for detecting and monitoring contact forces between a mapping catheter and the wall of the organ or vessel to permit faster and more accurate mapping, without being affected by electromagnetic interference generated by other equipment also used in the operation's room.

This can be accomplished by instrumenting a deformable catheter tip with at least two optical fiber sensors and with adequate software able to compute at a two- or three-dimensional force vector from the detected changes in the optical characteristics of the optical fiber sensors.

An example of implementation based on the use of 3 Fiber Bragg Grating sensors for strain detection and 2 FBG temperature sensors, is presented in this contribution.

6167-26, Session 6

Novel dual-channel fiber optic surface plasma resonance sensors for biological monitoring

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Fiber optic SPR sensors have drawn considerable attention over the past few years, currently most fiber optic SPR devices are used for single chemical parameter detection and usually omitted the compensating ability to avoid the unexpected effects that caused by the changes of instrumental or external testing conditions such as the thermal expansion coefficient t of optical material, fluctuation or shift of light source spectrum and sensitivity of spectrometer, the test condition changes of external environments as well as bulk refraction index variation in less controlled environments. Recently, multi-channel SPR sensors have attracted a great deal of attention due to their potential uses in the multi-analyte detection. Some multi-channel SPR sensors have been constructed from a prism or a light pipe containing sensing channels with recognition elements for detection of specific analytes, they are not suitable for remote in-situ multi-analyte and also their applications were mainly for analyte detections in liquid phase monitoring. In this study, we intent to develop a kind of practicable highly sensitive fiber optic SPR sensors for multi-analyst monitoring of both liquid and vapor analyte with self-compensating capability. Dual-channel fiber optic sensors based on surface plasmon resonance (SPR) for direct refractive index measurements are reported in this paper. We presented two dual-channel fiber optic SPR sensors based on flat-tip or tetra-taper tip structure with two SPR spectrum located on separate wavelengths that can be used for self-compensating refractive index monitoring of more than one biological samples. The prototyped sensors were fabricated and laboratory characterized. The preliminary experimental results demonstrate the characteristic responses of both SPR wavelengths from two channels are independently correspond to the refraction index changes of the detected samples or the temperature characters of external environment. The experimental results also confirmed us that for flat-tip based SPR probe, one sensing area can be used as a reference sensing channel which could compensating the unexpected effect from external temperature changes, it is possible to develop this kind of sensors as practicable high-sensitivity SPR instrumentation. Both of these designs could be extend into multi-channel biosensing devices that will have extensive applications for biological monitoring. This study demonstrates the general functionality of the designed dual-channel fiber optic SPR sensors for potential multi-analyst or self-compensating measurements in biological environment.

6167-27, Session 6

Chemical sensors based on temperature-responsive hydrogels

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In order to realize a new type of chemical sensor, a thermo-shrinking poly(N-isopropylacrylamide) (PNIPAAm) hydrogel with a solution concentration dependant swelling behavior was used as chemo-mechanical transducer. Commercially available pressure sensor chips with a flexible thin silicon membrane were employed as mechano-electrical transducer for the transformation of membrane deflection into an appropriate electrical output signal. The hydrogel itself was brought into a cavity at the backside of the silicon chip and closed with a cap. The sensor chip was bonded to a socket with inlet and outlet flow channels. The aqueous solution to be measured was pumped through the inlet tubes into the silicon chip cavity. The swelling or shrinking processes of the hydrogel were monitored by corresponding changes in the piezoresistance of an integrated Wheatstone bridge due to a stress state change inside a rectangular silicon membrane affecting proportionally the output voltage of the sensor. Since the sensor chip itself shows excellent stable properties, the long-term stability of the sensor is solely determined by the stability of the hydrogel characteristics.

The sensor's output voltage was measured during the swelling of the hydrogel under influence of water solutions with different organic and inorganic solute concentrations at different temperatures. It was found that the change in the gel volume phase transition temperature depends on the solution viscosity and the concentration of the additive affecting the stiffness of the polymer chain in the surrounding solution. The influence of an initial gel conditioning procedure on the signal value and the sensitivity of the proposed chemical sensors was investigated and the measurement conditions necessary for high signal reproducibility and long-term stability were determined.

6167-28, Session 6

Solid polymer electrolyte membrane flow sensor for tracheal tube

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Solid polymer electrolyte membrane (SPM) is a new type of material that works both as an actuator and as a sensor. It has unique characters of extremely light weight, controlled by low voltage, very fast response time, and versatility in fabrication into various configurations. We have developed a flow sensor unit using SPM. Nafion R-1100 resin was immersed to hydrolysis solution using a mixture of

dimethyl sulfoxide (DMSO), potassium hydroxide (KOH), and water. The membrane was placed in a molding pipe during the hydrolysis process; after this process, the membrane retained the molded shape throughout to produce desired shape and thickness of SPM. The pre-shaped membrane then was permeated in [Au(phen)Cl2]+ solution. After the immersion, the membrane was reduced with 5% Na2SO3 solution to perform Gold plating. The membrane was cut into a round shape to fit into the flow duct of a ventilator. Prepared SPM was fixed on a plastic pipe of diameter 22 mm and was connected to a ventilator circuit and driven by a ventilator (IMI T-Bird) with a pressure control ventilation (PCV) mode. Generated voltage developed by the membrane with the setting the maximum pressure from 5 cmH2O to 20 cmH2O was measured and amplified with an operational amplifier and a low pass filter with cutting frequency of 100 Hz. The waveform was recorded on an oscilloscope. SPM sensor demonstrated a biphasic response to the ventilator flow. In this setting, inspiration flow was detected as positive deflection while expiration flow was negative. The developed voltage was in order of several hundred μV. In addition, a sensor array unit with SPM was developed to attach inside a tracheal tube. This sensor unit detects the pressure change associated with respiratory flow. The flow sensor serves as (1) flow detecting sensor that alerts the operator if the tracheal tube was inserted to esophagus by mistake, (2) respiratory effort sensor that triggers the initiation of respiration cycle for the ventilator attached to a patient. A preliminary data for respiratory flow measurement demonstrated a proportional response to the pressure and the direction of flow was reflected on the polarity of the developed voltage. Thus, the sensor identifies the tract where the tracheal tube is placed: if the tube is placed in the esophagus, it does not detect bidirectional flow whereas if is correctly placed in trachea, it verifies with bidirectional signal. Also, the very fast response for very low initial pressure change, e.g., 2-3 cmH2O is ideal for detecting initiation of respiration.

6167-29, Session 6

Comparison of self-assembled nanocomposite thin film and optical fiber hydrogen sensors

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This paper compares the design, fabrication and performance of self-assembled nanocomposite and optical fiber-based hydrogen sensors. Both sensors are based on the physical displacement that occurs in Pd thin films due to the presence of hydrogen gas. Optical fiber-based hydrogen sensors based on Pd thin film coatings applied to both Fabry-Perot and fiber Bragg grating (FBG) strain sensing elements. The operation of these devices is based on the hydrogen-elicited extensional response of the Pd film, the corresponding changes in the length of the sensing elements, and the resulting changes in the phase or spectral reflectivity response of the elements, respectively. Performance limits of these devices are due to the strain response of the Pd films, the high modulus of the fiber sensor elements, and the minimum detectable signals of interferometric and spectral detection systems. Self-assembled Pd thin film sensors are entirely different. They are based on the self-assembly of Pd nanoclusters into sensor films on top of Metal RubberTM-type materials that change their electrical conductivity with extension. Unlike glass optical fibers, Metal RubberTM-type materials have a modulus as low as 1 MPa or lower, so do not significantly mechanically load the Pd film as it deforms. Limits on the performance of these sensors are the control over the percolation dynamics of the Metal RubberTM material and all of the disadvantages of amplitude-based detection techniques. This paper compares the performance of such sensors for hydrogen analysis in engineering systems.

6167-30, Session 7

Smart magnetic materials and magnetoresistive sensors in controlling of mechanical structures

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Materials named SMART ones in current literature play growing role in materials science and applications: “The definition of smart materials has been expanded to materials that receive, transmit, or process a stimulus and respond by producing a useful effect that may include a signal that the material is acting upon it. Some of the stimuli that may act upon these materials are strain, stress, temperature, chemicals (including pH stimuli), electric field, magnetic field, hydrostatic pressure, different types of radiation, and other forms of stimuli.” Smart Magnetic Materials (SMM) play an important role in this group of materials. SMM being subjected to research presented below include:

Materials changing their internal structure (Magneto-Rheological Fluids - MRF, Ferro-Fluids - FF, Magnetic Gels - MG, Magnetic Greases - MGS, Magneto-Rheological Composites - MRC);

Materials with fixed internal structure (Giant Magneto-Resisitive materials - GMR, Giant Magnetostrictive Materials - GMM, Giant Magneto-Caloric materials - GMC, Magneto-Rheological Elastomers - MRE, Magneto-Strictive Elastomers - MSE, Ferromagnetic Memory Alloys - FMA).

Effective application of Smart Magnetic Materials requires identification of their properties, mainly damping characteristics as function of mechanical parameters (stress, strain, frequency) as well as magnetic properties (magnetic field intensity). Last purpose entails generation of new constitutive equations and experimental methods needed for verification. Due to variety of materials we have confined ourselves to magnetorheological fluids (MRF), magnetorheological composites (MRC) and Giant Magnetostrictive Materials (GMM). Chosen examples are briefly presented below.

Possibilities of the Magneto-Rheological Composites MRC:

The MRC used for tests was created by soaking porous material of density 20 kg/m(c)$^{-}$ with Magnetorheological Fluid containing 85% mass ratio of carbonyl iron (diameter about 5 μm). It was adhered to plastic plate surface and inner surface of magnetic core that implied relatively small values of displacement. The experimental set-up used for applying, acquisition, processing mechanical and magnetic signals is shown and described precisely. Total influence of magnetic field and amplitude of deformation on damping in tested magnetorheological composite is presented. Examples of application are discussed.

Testing of the Giant Magnetostrictive Materials - GMM:

Tests were performed for cylinder made from rare earth elements alloy (Terfenol-D). High effectiveness in transforming magnetic energy into mechanical one (actuator) as well as mechanical into magnetic (sensor) requires experimental determination and identification. Original stand used in research allowed to fix mechanical and magnetic loads, measurement of signals and signal processing. The damper constitutes a main element of a system. Exemplary results of model identification comprising own experimental data are presented.

Magnetovision camera and applications:

The study was aimed to design a system for measuring the strength of magnetic field surrounding a ferromagnetic specimen subjected to cyclic (or static) loading. A new type of camera for monitoring the magnetic picture of specimen and other object was constructed. The measurement principle is based on the reverse magnetostriction effect (also called the Villari effect). No external magnetizing field is assumed; the entire magnetic effect is due solely to cyclic mechanical loading. The measuring arrangement is best suited for examining plane stress cases. The measuring set-up is made up a precision computer controlled X-Y positioner and a basis unit whose main element is a single magnetoresistor or an array of magnetoresistors. A digital processing system yields a quasi-continuous magnetic image of an object. Examples of application are presented.

6167-31, Session 7

A self-powered wireless sensor based on magnetic and piezoelectric composite material

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In many applications of wireless sensors, such as in rotating objects and embedded sensors in buildings, the sensor must be completely embedded in the structure for ever, with no physical connection to the outside and no power supply. A promising solution for long-term and long sensing distance is self-powered or energy harvesting sensors. Such sensors convert energy from existing energy sources within their environment into electrical energy. The ambient energy sources may be light energy, thermal energy, flow of liquids or gas, gravitation fields, mechanical vibration and electromagnetic field, etc. Due to the limitation of the application condition, the electromagnetic self-powered system may have more advantages than other self-powered systems and can be used in many specific fields.

The most important parameters influencing the design of self-powered system are its physical size and conversion efficiency. The size is dependent on the energy requirement and must be as small as possible, to be compatible with the general design objectives of MEMS. The magnet coil power generator and passive wireless SAW (surface acoustic wave) RF (Radio Frequency) powered tags are conventional schemes, however, they have extremely limited power and generally require either a large collection area or close proximity to the radiating source. Another composite sandwich transducer with PZT and magnetostrictive material has a small size, but it is the challenge of generating power from comparatively high RF radio frequency and high efficiency of energy harvesting.

This paper presents a new scheme of self-powered magneto-electric transducer with high-frequency magnetic and piezoelectric composite heterostructure material. Both the magnetostrictive material and the piezoelectric material convert the energy in resonant surface coupling wave modes. A surface wave transducer and a unidirectional transducer group (UDT) are created inside a ferromagnetic alloy and a piezoelectric structure, respectively, while propagating the unidirectionality

required for low loss and receiving the acoustic wave with higher efficiency. While the electromagnetic energy is collected from ambient-radiation sources, the resonant surface vibration in magnetic material may be energized. Then the UDT in piezoelectric material can receive and convert the surface wave to electric energy with high efficiency. Due to the exchanging energy concentrated on the surface and negligible leakage currents, this multilayer structure of magnetostrictive and piezoelectric phases shows a stronger electromechanical coupling and higher magneto-electric conversion efficiency than bulk composite. This work is devoted to investigations of resonant surface electromechanical effects in layered systems. Studies are important at magneto-mechanical-electric coupling in surfaces of layered structures and two types of resonances: ferromagnetic resonance for the magnetic phase and electromechanical resonance for piezoelectric component. As the most of energy is mainly distributed on surface of magnetic material and piezoelectric material, and the interaction energy is also on the surface between two materials, the energy loss in inner material can be decreased greatly and the conversion efficiency can be very high. After combining the device of energy transmitter and store, the self-powered wireless sensor can be used as micro-power supply in longer distance forever.

6167-32, Session 7

Surface control of cold hibernated elastic memory self-deployable structure

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A new class of simple, reliable, low mass and packaging volume, and cost self-deployable structures has been developed for use in space and commercial applications. Feasibility of this smart structure technology has been demonstrated previously by numerous experiments. This technology called “cold hibernated elastic memory” (CHEM) utilizes shape memory polymers (SMP) in open cellular (foam) structures. One of many potential of CHEM smart structure for space applications is its use for solar arrays, antennas, sunshields and solar sails as self-deployable multifunctional structures with embedded thin film electronics, sensors, actuators and power sources. This space application require a high precision deployment and surface accuracy. The CHEM structure could be slightly distorted by the thermo-mechanical processing cycle of compaction, deployment and rigidization as well as by thermal space environment. Therefore, the sensor system will be needed to monitor and correct the potential surface imperfection.

During these studies, the surface control of CHEM smart structures was demonstrated using a Macro-Fiber Composite actuator (MFC) developed by NASA Langley Research Center and the Army Research Laboratory. This flexible piezoelectric actuator was initially developed to control vibration and deformation in composite helicopter rotor blades. Here it was used to control and monitor the shape of CHEM structure. Prior to fabrication of a test structure, tests were performed to evaluate the optimum bonding materials and processes. The adhesive with the best bonding behavior was selected for fabrication of an experimental test CHEM structure with integrated MFC actuators.

The performance of actuator and recoverability of the original shape of CHEM structure were examined before and after thermo-mechanical processing cycles. Behavior of these smart structures was evaluated for rigidization characteristics and storage stability at RT prior to exposure to higher temperature. Thermo-mechanical processing cycles of compaction as well as deployment/shape restoration at elevated temperature were also demonstrated by subsequent tests. This paper will present details of processing and test conditions. The test results indicate that the MFC actuator performed well before and after processing cycles. It reduced some residue compressive strain that in turn corrected very small shape distortion after each processing cycle. The integrated precision strain gages were detecting only a small flat shape imperfection indicating a good recoverability of original shape of the CHEM test structure.

6167-34, Session 7

Wireless accelerometer network for process monitoring

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Lost Foam Casting (LFC) enables the production of complex castings while offering the advantages of consolidation of components, reduced machining, and recirculation of the casting mold material. In the process, a replica of the desired product is produced of blown polystyrene, coated in refractory slurry, and cast in a dense, unbonded sand mold. In order for the unbonded sand mold to fill into pattern holes and to provide sufficient confining force to prevent the advancing molten front from penetrating beyond the mold boundaries, the sand mold is produced by an overhead raining and flask vibration schedule that encourages fluidization and subsequent densification. The amplitude, frequency, and duration of the flask vibration as well as the rate of sand filling are critical parameters in achieving quality castings. Currently, many foundries use an often-lengthy trial-and-error process for determining an acceptable raining and vibration schedule for each specific mold and rely heavily on simple measurements and operator experience to control the mold making process on the foundry line. This study focuses on developing a wireless sensor network of accelerometers to monitor vibrational characteristics of the casting flask during the mold making stage of LFC. Transformations in the vibrational characteristics of the flask can provide a “signature” for indicating the condition of the unbonded sand mold. Additionally, the wireless nature of the sensor nodes enables the technology to travel across the foundry floor during the casting cycle eliminating the necessity of routine placement and setup.

6167-35, Session 7

Vibration control of polymeric composite plates using shape memory alloys

S. J. John, M. A. Hariri, B. Veeramachaneni, P. Trivailo, RMIT Univ. (Australia)

Vibration and resonance of plates are well known problems in designing and analysis of mechanical structures. While these problems are considered during the design process, significant amount of research has been directed to handle the unforeseen loading situations which may lead to catastrophic events. Different types of techniques (passive and active) were developed to prevent these events. Among these techniques, the implementation of the smart materials such as Shape Memory Alloys (SMAs) and piezoelectric ceramics gained importance for controlling the vibrations through damping or altering the resonant frequencies of the parent structures. Composite materials have become major players in building modern and advanced structures especially plates as a consequence; the development of smart composite structures emerged as an area of high interest. In this paper, the feasibility of SMA wires in controlling the vibration of composite plates through altering the strain energy and hence the natural frequency is investigated. The effect of placing the SMA wires in different directions (longitudinal and angularly transverse) over the composite plates will be studied. Computational and experimental work will be conducted to develop the control strategy to control combined vibration situations. Strain energy analysis of the composite panel using laminate theory considerations was used to relate the strain energy alteration in the panel as a result of the SMA actuation to its effect on the laminate stiffness.

6167-51, Poster Session

A new heart monitoring system developed with piezoelectric film sensor

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This article is concerned with the employment of PVDF piezoelectric film in the sensor to detect the weak physiological signals, combined with electrocardiograph, to establish the dynamic heart monitoring system. Using a kind of impedance converter technology, which makes the voltage enlarged easily, can decrease the output impedance of the piezoelectric sensor. The system consists of a piezoelectric sensor with electrodes detecting the heart’s signals, the appliancation and a recorder connected with personal computer and special software for recording and analyzing the data of the heart’s signals in wide frequency spectrum from 20 Hz to 5 KHz. The system will alert doctor or patient to the abnormal signals. According to our experience the system is helpful in screening of the man’s heart sounds. It is more significant that the system is thought to be helpful in the orientation and evolvement of myocardial infarction and myocardial ischemia. Further studies to evaluate the clinical value of the system are in progress.

6167-52, Poster Session

Experimental measurement of fiber optic strain sensor

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Optical fiber as a sensing element has been studied for over a decade. The fiber optical strain sensors possess several advantages such as light weight, small dimension, high temperature endurance, dielectric nature, and immunity to electromagnetic interference, that meet the basic requirements to be a smart structure sensing element. The accuracy of the strain measured by the optical sensor is highly dependent on the bonding characteristics among the bare optical fiber, protecting coating, adhesive layer and host structure. As a sensor, it is expected that the strains between the optical fiber and host structure are the same. However, due to the existence of the adhesive layer and protecting coating, part of the energy would convert into the shear deformation. Thus, the strain of the optical fiber is different from the host structure. In this paper, three experimental tests namely three-point bending, four-point bending, and uniaxial tensile, are performed to reveal the differential strains between the fiber-optic sensor and test specimen. Mach-Zehnder interferometric type fiber-optic sensor is adopted to measure the strain. Incident light is separated into two components propagating along two

distinct paths named as sensing arm and reference arm, respectively. The sensing arm is bonded to the host structure subjected to strain field, reference arm is strain free. The resultant optical intensity will be a sinusoidal function. The optical phase difference between the sensing and reference arms is induced by the measurand (strain) field. The optical intensity is converted to electric voltage by a photodector. The direct peak counting method is used to calculate the induced strain in the fiber-optic sensor. An electric strain gauge is attached to the test specimen to measure the strain in the specimen. Experimental results show that the strain measured at the optical fiber is lower than the true strain in the test speimen. The percentage of the strain in the test specimen actually transferred to the optic fiber is dependent on the bonded length of the fiber. Parametric study shows that the longer of bonded length the more strain is transferred to the optic fiber.

6167-53, Poster Session

long-term monitoring FBG-based cable load sensor

Z. Zhou, Harbin Institute of Technology (China)

Stay cables are the main load-bearing components of stayed-cable bridges. The cables stress status is an important factor to the stayed-cable bridge structure safety evaluation. So it's very important not only to the bridge construction, but also to the bridge structure in-service long term safety evaluation. How to measure the cable force? The key is to choose an effective sensor, which can meet the long time durability and measurement demand. FBG, for its great advantage of corrosion resistance, absolute measurement, high accuracy, electro-magnetic resistance, quasi-distribution sensing, absolute measurement and so on, is the most promising sensor, which can cater for the cable force monitoring. In this paper, a pressure sensor has been developed, which is made up of a bushing elastic supporting body, 4 FBGs uniformly-spaced attached outside of the bushing supporting body, and a temperature compensation FBG for other four FBGs, more over a cover for protection of FBGs. It's analyzed the sensor measuring principle, and gotten the relationship equation of FBG wavelength shifts and out force. From the calibration result, the pressure sensor has excellent linearity of out force and FBG wavelength shifts, and repeatability, which is suitable for force measurement. So this kind of pressure sensor makes the cable force long-term, real time monitoring into reality.

6167-54, Poster Session

Early-age monitoring of cement structures using FBG sensors

Z. Zhou, C. Wang, Harbin Institute of Technology (China)

With more and more widely used of the cement-based materials such as neat cement paste, cement mortar and concrete in structures, people want to see what their performances like. As is known, the working performances of cement-based materials are affected very much by the hardening process of the early-age. But the common measuring techniques on the early curing of the cement-based materials are limited for some of the disadvantages, such as: difficulties in embedding sensors inside the concrete, limited measuring points, poor durability and interference of electromagnetic wave. So in this paper, according to the sensing properties of the Fiber Bragg Gratings sensors and self-characters of the cement-based materials, we have successfully finished measuring and monitoring the early-age inner-strain and temperature changes of the neat cement paste, concrete with and without restrictions, mass concrete and negative concrete systematically. We developed three types of FBG sensors suitable for being embedded and monitoring in cement-based materials, while the embedding technology and the embedding requirements of FBG sensors in cement-based materials are also discussed. The results show that FBG sensors are well proper for measuring and monitoring the temperature and strain changes including self-shrinkage, dry shrinkage, plastic shrinkage, temperature expansion, frost heaving and etc inside different cement-based materials during their early-age.

During the construction of the Third Nanjing Yangtze Bridge, 250 FBG sensors were applied to monitor the temperature distribution of the mass concrete. The monitoring results of temperature distribution and its changes with time, environmental temperature, setting retarder, and cooling water agree well with that from experience and qualitative analysis.

This technique provides us a new useful measuring method on early curing monitoring of cement-based materials and greater understanding of details of the hardening process.

6167-56, Poster Session

Noninvasive measurement of on-chip RF field strength with application to RFID systems

B. Jamali, The Univ. of Adelaide (Australia)

In the modern world of increasing miniaturization, electronic devices are getting smaller and smaller with more transistors packed into a smaller area. Continual scaling of devices into the deep-submicrometer regime has resulted in the need for studying the effects of electromagnetic signal fed to sub-micron transistors.

The importance of this work is the incorporation of RF detectors on chip. That would allow a direct analog microwave level measurement to be implemented on a single chip along with the rest of the circuit. Integrating detectors with amplifiers allows non-invasive on-chip measurements. In this paper we start with a brief survey of different power detection techniques and then will focus on methods of measuring electromagnetic signal strength at chip level. Knowing this enables a designer to employ strategies to mitigate its destructive effects more rapidly.

6167-57, Poster Session

Methodology and device in measuring thickness of thermoplastic tape in real time

Y. Chen, X. Chen, C. R. Liu, Univ. of Houston

Thermoplastic pavement marking materials (TPMM) provide delineation on highways around the world. The thickness of TPMM on pavement is a very important parameter to control the quality of TPMM, calculate durability of TPMM, and provide information for the maintenance and replacement of TPMM. Traditionally, the thickness measurement is conducted by using pre-embedded plates and measuring the thickness of TPMM after spraying of the marking materials. This method is labor intensive and cannot obtain a continuous-thickness profile. Developing an automatic thickness measurement system for marking materials is critical to pavement management and public safety.

The measurement system developed in this dissertation uses laser devices to detect the thickness of TPMM. A dedicated digital laser signal processing circuit is developed to restore thickness information. Both optical and electrical filtering techniques are applied in the design. The thickness measurement system includes two versions: (1) a pushcart measurement device and (2) a vehicle-mounted measurement device, which provide continuous real-time thickness measurement of TPMM. Both devices consist of two major parts: a hardware system to measure the thickness of marking materials using a laser triangulation technique, and a software package to analyze and process the measured data in real time.

Lab and field tests under various conditions with marking materials on real pavement surfaces were conducted. The test results showed that the measurement system is capable of reaching the resolution of 5 mils on pavement. The developed system for thickness measurement of TPMM has a 267 KHz working frequency, which is the highest among similar devices. The high speed allows the system to provide higher accuracy and more flexibility in various applications.

6167-58, Poster Session

Simulation, modeling, and application of ground-penetrating radar in pavement dielectric constant and thickness measurement

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Ground penetrating radar (GPR) is a non-destructive continuous electromagnetic (EM) detection technique, with wide applications in the civil and environmental parameter measurements. Applied to the highway pavement quality evaluation and maintenance, the GPR can provide pavement condition and soil property characterization. This technique is based on the measurement of the travel time and reflection amplitude of a short EM pulse, which is transmitted through the medium and reflected by the dielectric discontinuity interface. Such time and amplitude of the reflected signal is a function of the medium properties: dielectric constant, conductivity, thickness and moisture content.

Most thickness measurement for GPR is based on the priori knowledge of the dielectric constant of the pavement materials. However, the changes in pavement materials and moisture conditions make the fixed dielectric constant based on the manual estimation inaccurate. And actually, the dielectric constant is also an important parameter in such applications. For some GPRs, the dielectric constant can be estimated by using the surface reflectivity information. Such method needs additional at least one time prior measurement for the dielectric constant estimation, and the result is used for further continuous measurements in the similar environment. So this method is also not a real time solution. And for a ground coupling GPR, the method based on the surface reflectivity is not applicable.

In this paper, new methods are introduced to measure pavement dielectric constant and thickness accurately by ground coupling GPR at the same time. For different GPR types, different methods are implemented. For low frequency pulse radars, such measurement is based on the time shift between the air wave and the underground surface wave. The existence of the underground surface wave

has not been used in the GPR applications. In this paper, the existence of such underground surface wave is explained physically and verified by numerical simulation results. Also the application condition of this method and relationship with pavement structure are discussed. For high frequency FMCW radars, the signals take different paths. Here the model for the ray path is set up based on the theoretical derivation and simulation. Measurements based on unrelated ray paths and minimum error theory are introduced. Finally, applications and field test results for pavement evaluation are presented.

Compared to the air launched mode, the ground coupled mode is complicate because of the coupling effect between the antenna and ground. In this paper, simulation results reveal the ray path for such complicate mode. And by these two methods, focusing relatively for the low frequency pulse radar and high frequency FMCW radar, the measurements of pavement dielectric constant and thickness for ground coupling radar can be implemented accurately in real time without prior knowledge.

6167-59, Poster Session

Novel strain sensor for steel rebar or cable based on FBG

Z. Zhou, Harbin Institute of Technology (China)

The feasibility and advantages of a new kind of sensor on steel rebar or cable measuring based on FBG are discussed, Which can be easily installed in structures. And the sensing properties of this kind of new sensor under dead load are tested. The experimental results and theoretical calculation show that this kind of sensor is proper to be used in steel rebar or steel cable measuring, even long-term health monitoring.

6167-60, Poster Session

Defect classification of highly noisy NDE data using a linear discriminant classifier

K. F. Goebel, GE Global Research; J. Celaya, Rensselaer Polytechnic Institute; V. Avasarala, The Pennsylvania State Univ.

Condition monitoring in solid structures involves identification of defects that impact the normal equipment functioning. Advanced signal processing techniques are required to determine the relationship between system condition and sensor signals. Non-destructive evaluation (NDE) techniques typically rely on multi-sensor data fusion, since the information provided by a single sensor may not be accurate or adequate to estimate system condition. Typical systems for condition monitoring involve feature extraction from the sensor data and pattern recognition algorithms that operate on the extracted features to characterize the state of the system. To maximally exploit sensor information, sensor information is transformed into various domains, where different features are extracted with the potential of providing (or at least contributing) to the desired characteristics. Examples are frequency domain features like spectral analysis and time domain features like mean value, kurtosis etc. Performance of pattern recognition algorithms is contingent on quality of sensor data and the number of training samples available. In many practical applications, NDE sensor data is highly noisy and number of training samples available is limited. In such circumstances, the choice of pattern recognition algorithm and features used for classification become crucial to the success of NDE. In this paper, we present a feature extraction, evaluation and classification approach that was used to assess highly noisy sensor data from a NDE field study. The goal was to differentiate between two types of defects occurring in a solid structure. Multiple, heterogeneous NDT sensors were employed to examine the solid structure. Initially, areas of potential defects were marked using a c-scan visualization tool that exhibited sensor information from all the sensors. Sensor validation techniques were used to select the best available sensor that had the least noise effects and the best defect signature in the region of interest. A very large number of features that possibly exhibit some separability between the two kinds of defects were formulated and extracted from the sensor data. Next, we employed separability measures and correlation measures to select the most promising set of features. Since the number of data was small, particular care had to be taken to avoid over fitting. We experimented with two different classifiers: CART decision tree and b) linear discriminant classifier that were tuned to a set true positive rate using the Neyman-Pearson criterion. As expected, CART performed better on the available data, but an analysis of the decision boundaries revealed the problem of overfitting. Thus, the linear discriminant classifier was chosen over the decision tree algorithm for the NDE tool.

6167-61, Poster Session

Auto-synchronized laser scanning range sensor for thermoplastic pavement marking material thickness measurement

W. Sun, C. R. Liu, Univ. of Houston

Pavement marking materials provide delineation on highways around the world. The condition of the marking materials is very important for the driver's safety as well as the comfort and the driving expenses. Currently thermoplastic pavement marking materials (TPMM) are widely used in states. Measuring the thickness of TPMM on pavement is an essential index to monitor the contractors, calculate durability of marking materials, and provide better information for the pavement marking evaluation.

In recent years to measure the thickness of TPMM, a procedure involving pre-embedded plates sprayed with the marking materials has been widely accepted. This method is labor intensive, and cannot obtain a continuous-thickness profile. Therefore there are demands to develop a high-speed automatic measuring system for determining the thickness and uniformity of marking materials.

In this paper, a laser range sensor based on auto-synchronized laser scanning is proposed for the thermoplastic pavement marking material thickness measurement. Compare to classical triangulation method, this approach doesn't scarify the system resolution for large field of view and it is more suitable for highway speed measurement. To achieve high speed measurement, PSD (Position Sensitive Detector) is used in the prototype system instead of CCD (Charge Couple Device) in traditional auto-synchronized system. The standoff distance and transverse scan range of the prototype system both are 2 feet. The lab test results show that the prototype system can measure the thermoplastic type thickness with error in 2.5mil at laser scanning rate up to 50Hz.

6167-62, Poster Session

Development of the RF soil moisture sensors

J. Cheng, J&M Biotek International LLC; X. Chen, J. Li, C. R. Liu, Univ. of Houston

Accurate measurements of soil water content are important to land activities, especially those involving agriculture, forestry, hydrology, and engineering. In this paper, a theoretical and experimental study of the microwave moisture measurement sensors is conducted.

A phase-based moisture sensor system using a transmission line sensor is designed. The amplitude of the transmission measurement is a strong function of the conductivity (loss of the media) and the imaginary part of the dielectric constant, and the phase is mainly a strong function of the real part of the dielectric constant. One can obtain the soil moisture information from measuring the phase shift of the transmitted waves.

Microstrip resonator sensors are also studied and fabricated. The effective permittivity will change if a dielectric material is present near the substrate of the resonator, which causes the shift of the resonant frequency. The measured data show that both sensors are sensitive and accurate.

6167-63, Poster Session

Aircraft sensor validation monitor and state estimator using artificial intelligence

S. Kwak, SenAnTech, Inc.; H. Yoon, The Ohio State Univ.

A new Sensor Validity Monitoring, Verification and Accommodation (SVMVA) scheme for flight control systems is developed. An artificial intelligence algorithm based on the vector quantization technique is employed as the state estimator. A new input vector optimization technique is applied to enhance the SVMVA. The feasibility of the system is demonstrated through numerical simulations with flight data obtained using an in-house F-16 aircraft simulator. The results show that the SVMVA can detect the failure of sensors and mask them accurately.

6167-64, Poster Session

Modal analysis using the Bessel harmonics of an extrinsic Fabry-Perot interferometric sensor (EFPI) and neural networks

A. M. Abdi, College of Optical Sciences/The Univ. of Arizona; S. E. Watkins, Univ. of Missouri/Rolla

A demodulation system employing neural networks is used to process the nonlinear signal from an extrinsic Fabry-Perot interferometric (EFPI) sensor. A sinusoidal strain is theoretically shown to produce well-defined Bessel harmonics in the EFPI signal. The neural network demodulator (NND) uses a Fourier Series Neural Network to separate the Bessel harmonic components of the EFPI signal and a Back-Propagation Neural Network is used to predict the strain levels through the analysis of the Bessel harmonics. The NND is first simulated in a computer program and then actually employed in an experimental setting to determine the frequency response of a 25 cm composite cantilever beam. A function generator was used to drive a PZT actuator attached to the composite beam and resulting

periodic strain was measured by the EFPI; the frequency of the composite beam was varied between 10 Hz and 900 Hz. The NND demodulated the EFPI signal and determined the frequency response of the composite beam. The results show that the NND accurately reproduced the natural frequencies and mode shapes of the cantilever beam.

6167-65, Poster Session

The use of hybrid automata for fault-tolerant vibration control

C. R. Byreddy, K. D. Frampton, Vanderbilt Univ.

The purpose of this work is to make use of hybrid automata for vibration control reconfiguration under system failures. Fault detection and isolation (FDI) filters are used to monitor an active vibration control system. When system failures occur (specifically parametric faults) the FDI filters detect and identify the specific failure. In this work we are specifically interested in parametric faults such as changes in system physical parameters; however this approach works equally well with additive faults such as sensor or actuator failures. The FDI filter output is used to drive a hybrid automata which selects the appropriate controller and FDI filter from a library. The hybrid automata also implements switching between controllers and filters in order to maintain optimal performance under faulty operating conditions. The biggest challenge in developing this system is managing the switching and in maintaining stability during the discontinuous switches. Therefore, in addition to vibration control, the stability associated with switching compensators and FDI filters is studied in detail. Furthermore, the performance of two types of FDI filters are compared: filters based on parity relations and so called "Beard-Jones" filters. Finally, these simulations help in understanding the use of hybrid automata for faulty-tolerant control.

6167-66, Poster Session

Optimization of passive piezoelectric vibration shunt control based on strain energy transfer and online frequency detection

S. J. John, J. J. Cao, T. Molyneaux, RMIT Univ. (Australia)

Mechanical vibration control has long been a subject of engineering research. Recently, the use of smart material-related components for vibration control has become an alternative to traditional vibration control techniques. It has many advantages such as lighter overall weight, smaller size and lower cost. They are especially suitable where traditional techniques cannot be applied due to weight and size restrictions. Passive vibration shunt control using piezoelectric material (PZT) and an electrical network can remove considerable amount of vibration energy from flexible structures when being properly tuned. In this paper, an analytical study of the passive piezoelectric vibration shunt control on a beam structure by using the Hamilton's principle, Galerkin's method and finite element analysis (FEA) method is presented. However, the efficiency of such vibration control method relies on the optimization of vibration energy transfer between a structure and piezoelectric material. In the paper, strain energy transfer within the composite material, which is made of two layers of different materials, and how do the material property, geometry sizes of the layers affect the strain energy transfer are analyzed. It indicates that neutral axis of the composite material has significant influence on the optimization of strain energy transfer between the structure and PZT. Simulation results using a finite element analysis software package - ANSYS(r) as well as experimental results are presented in the paper. Since the passive vibration shunt control circuit functions as a bandpass filter that has narrow bandwidth, it is very sensitive to frequency shift of the structure to be controlled. However, in reality, the natural frequencies or resonant frequency of flexible structures often vary somewhat due to environment change such as boundary conditions, temperature variation and material. The effectiveness of the vibration control will be significantly reduced when the frequency of the shunt circuit does not match the natural frequency of the structure to be controlled. It is important to have a control algorithm that can determine the natural frequency of the structure in real time therefore the shunt circuit can track the change of natural frequency. In the paper, an algorithm of estimating and tracking the resonant frequency of flexible structures using adaptive notch filter (ANF) is presented. The structure of the filter is synthesised from digital lattice all-pass filters which are lossless and computational efficiency building blocks. The resistor-inductor (R-L) piezoelectric shunt circuit is basically a R-L resonant circuit which uses an inductor to cancel the inherent capacitive reactance of piezoelectric material. The frequency of the shunt circuit is controlled by adjusting the value of the inductor. Since the value of the inductor is usually large, especially for low frequency control, it often uses a synthetic inductor which is made of operational amplifiers, capacitors and resistors. The value of the inductor is determined by the values of capacitors and resistors. With an online frequency detection algorithm, the inductor value is possible to be adjusted in real time by some kind of controllable capacitors and resistors to compensate the frequency shift of structures.

6167-67, Poster Session

The equivalent circuit parameters of piezoelectric transducers embedded in concrete

Y. Chen, Y. Wen, P. Li, Chongqing Univ. (China)

A scheme for monitoring concrete structure has been previously proposed by embedding PZT ceramic into concrete. By measuring the equivalent circuit parameters of the embedded piezoelectric ceramics, the structural state may be interrogated. However, for a long time, it has been disturbing that piezoelectric elements are not only sensitive to mechanical settings but also sensitive to a lot of surrounding factors such as temperature, humidity. Thus, it is commonly thought that it's almost impossible to embed piezoelectric devices into rough concrete structure to perform repeatable and detectable sensitivity even though embedding piezoelectric material into other composite has proved to be a feasible way to produce smart material or structure.

Here, a dozen of experiments have been conducted to characterize the stress and temperature dependence of PZT ceramic embedded in concrete. In experiments, concrete specimens with a dimension of 100Å~100Å~100mm are repeatedly tested under varying stress or temperature. Two kinds of PZT ceramics (PZT-4 and PZT-5H) which have a same dimension of ϕ25Å~2mm are embedded in concrete specimens. The stress and the temperature fields are separately established by a stress testing machine (SHIMADZU AG-I 250 Universal Testing Machines) and a temperature chamber (SDJ-402). In the temperature experiment, the PZT ceramics free of embedment and the concrete specimens with embedded PZT ceramics are together placed in the temperature chamber, and experience a temperature change from -30°C to 120°C. Because the stress experiments are carried out at room temperature, where the temperature can be taken as time-invariant, the variation of the parameters can be taken as only resulting from the stress variation. However in temperature experiments, the temperature variation also introduces the stress variation by changing the volume of the concrete specimens. In addition to the temperature caused stress, there is another kind of stress which takes its effect. Since the PZT ceramics are embedded, the ceramics have been affected by the stress accumulated in the process of concretion of the concrete specimens. It is found that, some of the parameters change their values a lot after the concretion process finished. We also monitored the parameters during this process. The time-dependence of the parameters is found to show a near-exponential curve in 20 days of concretion. At the end of the concretion, the parameters reach their steady values. The stress and temperature experiments reveal that all the equivalent circuit parameters of two kinds of PZT ceramics are sensitive to both stress and temperature. Moreover, interestingly, it is found that the characteristic frequencies including resonance and anti-resonance frequencies respond only to temperature. It is of great significance to amend the stress measurement. Consequently, by analysing and synthesising the equivalent circuit parameters, it is possible to acquire the specific signature only connected with the surrounding mechanics from PZT ceramics embedded in concrete.

6167-68, Poster Session

Hybrid biotic/abiotic biomolecular nanofactory

H. Choi, C. D. Montemagno, Univ. of California/Los Angeles

Living organisms carry on certain life processes, resulting from the sub-cellular level chemical processes, which are of major interest in physiology. Each cell is a basic structural and functional unit of an organism. As such, different types of cells carry out various kinds of fundamental chemical reactions to create and maintain life processes. In addition, as a result of the laws of nature, they provide an excellent example of optimally functioning machine. Therefore, interfacing biochemical processes with nanotechnology promises both a structure and a function to gain high-order functionality. This creative process starts from the understanding of how life works and is accomplished through the modification of nature to our needs. This integrative technology implies the engineering functionality of living systems.

Typical structure of a cell can be divided into plasma membrane, cytoplasm, and nucleus. The plasma membrane is a flexible barrier that is formed by self-assembly of lipid molecules, separating the cell's internal environment from the external environment. Transport of materials across the cell wall is an essential process to the life of a cell, which is performed by membrane proteins. While in vitro experiments can recreate the natural environment of membrane bound proteins, lipid membranes have an innate instability undesirable for the production of useful bioelectronic devices. For this reason, much attention has been drawn to the self-assembling, amphiphilic ABA triblock copolymer membrane/vesicle as an artificial cell membrane in the fabrication of biosensors and nano-containers [1].

Presented is the nanosized hybrid biological/inorganic factory, artificial organelle,

where programmed biochemical reactions take place in response to the external stimulus, resulting in the production of biomolecules. We have reconstructed a mitochondrial ATP synthesis process through the orchestration of two proteins (bacteriorhodopsin, F0F1-ATP synthase) reconstituted into the nano-size polymer vesicles, where photon energy is converted to biological energy. It is expected that hybrid systems with engineered functionality will have wide applications in a number of fields ranging from in vitro investigation of cellular metabolism to the synthesis of a new class of functional smart materials.

[1] H.-J. Choi, E. Brooks, and C. D. Montemagno, Nanotechnol. 2005, 16, S143.

6167-69, Poster Session

Fiber optic Bragg grating sensors for high-precision structural deformation control in optical systems

U. C. Mueller, T. Zeh, A. W. Koch, H. J. Baier, Technische Univ. München (Germany)

Fiber Optic Bragg grating (FBG) sensors are inscribed into optical fibers. They show promising capabilities in the measurement of strain and temperatures in structures. Their multiplexing capability allows the simultaneous measurement of these quantities at many locations of a structure. In this work, the potential of FBG sensors for high-precision deformation control in optical applications is investigated. This study contains an experimental test rig with a simply supported steel beam. The beam was designed in order to represent the stiffness of an optical mirror made by Cesic. The deflection of this beam is controlled by an actuator. The measurement of the deflection is done using capacitive displacement sensors with a resolution < 1 nm. FBG sensors are mounted onto the structure to record the strain. It is being investigated to what level of accuracy FBG sensors can be used to reconstruct the displacement information.

Different methods in order to increase the accuracy are discussed: decreasing the sensor noise by oversampling and increasing the number of sensors. Tests were performed using different diffraction-based interrogation techniques for the wavelength detection: a CCD-based and a PSD-based high-speed FBG sensor system which - to our knowledge - has not been used for an application of this kind, so far. A comparison of both systems discussing the weaknesses and strengths is given for the recording of mechanical strain < 1 μm/m. The experimental results so far showed that a resolution of < 60 nm for the deformation control using FBG sensors can be achieved. This study shows an interesting application potential for FBG sensors in structural deformation control for various fields such as optics or high-precision tooling machines.

6167-70, Poster Session

Temperature and strain monitoring over 200km with meter spatial resolution using fiber optic distributed Brillouin scattering analysis

M. Niklès, F. Briffod, Omnisens S.A. (Switzerland)

The authors have developed and demonstrated a method for extending the reach of a Brillouin OTDR interrogating system such that sensing sections of conventional length (approximately 25km) can be successfully interrogated from distances well in excess of 100km without having to compromise on the performance. With a single instrument, more than 250km of sensing fiber can be monitored to within 1 meter resolution. By this means, temperature and strain profiles may be measured along pipelines or flow lines looking at leakages, deformations, blockage, etc.

6167-36, Session 8

Self-assembled Metal Rubber(TM) mechanical sensors

R. O. Claus, Virginia Polytechnic Institute and State Univ.; A. J. Hill, J. H. Lalli, M. Homer, NanoSonic, Inc.

This paper describes progress in the development and demonstration of mechanical sensors fabricated using so-called self-assembly manufacturing processes. The room-temperature self-assembly process allows the formation of multilayer materials from a variety of molecules, including metallic and ceramic nanoclusters, polymers and others. Recent work had demonstrated the ability to combine electrically conducting metal nanoclusters with advanced polymers in ultralow modulus (less than 1 MPa) multilayer materials using this process. The electrical conductivity of such materials is comparable to that of bulk metals, and is observed to vary with mechanical strain if the volume percentage of the nanoclusters is near the electrial conductivity percolation limit. Of interest, these electrically conducting and highly elastic materials may be strained to nearly 1000% (one thousand percent) and relax back to their original size and shape. This allows 1) the measurement of very large strains that are typically difficult to quantify using conventional strain measurement systems, and 2) minimal mechancial loading on flexible materials to be measured. Rigid foil strain gages and optical fiber strain sensors typically cannot allow this type of large deformation without failure, and/or delamination from the substrate surface.

The paper will discuss results of large strain measurement and also multiplexing methods used to remotely address several such sensor elements using wideband RF techniques.

6167-37, Session 8

Intrinsic polymer optical fiber sensors for high-strain applications

S. Kiesel, P. Van Vickle, K. J. Peters, T. Hassan, M. Kowalsky, North Carolina State Univ.

This paper presents experiments to characterize the performance of polymer optical fibers (POF) for such high strain applications. POFs provide a maximum strain range of 6-12%, are more flexible than silica optical fibers, and are more durable in harsh chemical or environmental conditions. Previous researchers have used multimode POFs for the detection of cracks or the change in dynamic response of a structure by interrogating the intensity of lightwaves propagated through the POF. The propagated intensity is diminished due to bending of the fiber or necking of the fiber at high applied strains. These measurements, while successful, are limited in application due to the presence of multiple modes and the lack of detailed, quantitative knowledge on the opto-mechanical response of the POF.

Recent advances in the fabrication of singlemode POFs have made it possible to extend POFs to interferometric sensor capabilities. However, several challenges make the application of the POF interferometer more difficult than its silica counterpart. These include: (1) the nonlinear stress-strain response of the polymer; (2) the finite deformation of the POF cross-section at high strain values; (3) nonlinear strain optic effects in the polymer; and (4) the attenuation with strain of the POF. In order to predict the response of the sensor a second-order (in strain) photoelastic effect is derived and combined with the second-order solution of the deformation of the optical fiber when loaded. Based on these derivations, the number of independent sensor sensitivities (or coefficients) are determined and a series of experiments proposed to determine these sensitivities. It is determined that for the small deformation region four constants are required (2 mechanical properties and 2 photoelastic properties) and for the large deformation region six additional constants are required (2 mechanical properties and 4 photoelastic properties).

This paper also presents the results of the calibration experiments applied to a singlemode POF and demonstrates its use as a strain sensor. Finally, the paper discusses the relative sensitivity of the sensor to various loading conditions.

6167-38, Session 8

New kind of FBG-based crack (large strain) sensor

Z. Zhou, Harbin Institute of Technology (China)

Optical Fiber Bragg Grating (OFBG) is now widely accepted as smart sensor due to its advantages of electric-magnetic resistance, small size, distributed sensing, durability, and so on. However, to our regret, the bare FBG can only stand 3000~5000, which can not satisfy the need of practical strain monitoring of infrastructures, especially for the damage detection, such as crack and large strain. In this paper, new technique of sensitivity-decreasing of FBG strain sensor has been brought forward and a new kind of FBG-based crack sensor is developed. The novel FBG-based crack sensor (also named large FBG strain sensor) can detect 100000 at maximum, almost 20mm crack at the calibration length of 20 centimeter, and the accuracy can reach 0.002mm. The new kind of crack sensor is proper for crack detection of long term structural health monitoring of infrastructures.

6167-39, Session 9

A simple method to identify the spatial location complication due to the transient phonon relaxation on the Brillouin loss spectrum

X. Bao, Q. Yu, F. Ravet, L. Chen, Univ. of Ottawa (Canada)

Distributed sensors based on Brillouin scattering has drawn increasing attentions due to their capability of measuring strain and temperature continually over a large distance. The measurement accuracy in temperature, strain and location has been greatly improved over the past years. For a non-uniform distributed strain or temperature, it is important to map the distributed strain or temperature with accurate location using multiple peaks fitting method.

Here we report the compound Brillouin spectra at the location much further than the pulse length from the boundary of two fiber sections. Our study indicates that it results from the transient phonon field created by the pump and pulsed probe signal through the Brillouin scattering process, and then the DC of the probe sig-

nal is reflected from it in the Brillouin resonance frequency region and re-join the pump signal at the time and location beyond the pulse coverage length. When the DC level of the probe signal in the Brillouin loss spectrum is comparable to the peak power of the probe, we could observe the AC pump power increment spectral feature (opposite of the Brillouin loss signal) in the different Brillouin resonance region. The detected AC pump signal in the Brillouin loss spectrum is the net results of the DC of the pulsed probe and pump signal reflection from the transient phonon field. Such transient field then decay or relax to the noise level at the time scale longer than normal phonon lifetime (10ns) depending on its strength. This phenomenon has not drawn attention because the transient phonon relaxation effect was considered due to the strain (temperature) gradient, or the pulse covering of the boundary. Particularly when the pulse width is comparable with the phonon relaxation time (10ns in silica fiber).

This is contributed by the reflection of the DC level of the probe pulse and CW signal of the pump by the transient phonon field, which lasts longer than the phonon lifetime (~10ns). We observed 65ns phonon relaxation time for two temperature/strain sections. This prolonged relaxation time depends on the pump and probe powers. We propose a new criterion to determine the boundary, which is the 2nd order partial derivative of Stokes signal with respect to frequency and position shows a maximum or minimum at the boundary between two different strained sections.

The second derivative procedure has been used in spectroscopy signal processing to find peaks of spectrum (second derivative of amplitude with respect to frequency). Here, the derivative is relative to frequency and location, rather than frequency alone, because the distributed Brillouin sensor needs both location and spectrum information related to strain or temperature.

This idea has been used to locate the boundary of different stress regions. Knowing the boundaries we then fit the Brillouin spectrum at the middle between them to get the strain value. This allows a location accuracy of between 5-10 cm, which is shorter than the pulse length of 20 cm used in the experiment. The lowest detectable Brillouin frequency difference between two strain sections is 1.2 MHz.

6167-40, Session 9

Combined Raman and Brillouin scattering sensor for simultaneous high-resolution measurement of temperature and strain

K. A. Brown, A. W. Brown, B. G. Colpitts, Univ. of New Brunswick (Canada)

Recently, strain and temperature measurement results using the first ever spontaneous Brillouin and Raman scattering based fiber optic sensor have been reported. This contribution reports the performance results of a combined Brillouin and Raman sensor used to measure strain and temperature simultaneously. This sensor is based on the combination of a BOTDA loss-based Brillouin sensor and a spontaneous Raman scattering based sensor, which has not been previously reported to date. We have implemented the combined sensor system for operation over useful sensing lengths and show significantly improved temperature and strain accuracy along with superior spatial resolution. Measurements of temperature and strain on a beam in an outdoor environment are given. This combined sensor system is shown to be capable of separating temperature and strain effects which previously limited Brillouin systems in some applications.

6167-42, Session 9

Integration of distributed strain and temperature sensors in composite coiled tubing

D. Inaudi, B. Glisic, Smartec SA (Switzerland)

Composite coiled tubing is an emerging technology in the oil & gas sector that presents important advantages compared to the steel coiled tubing and conventional drilling. The composite tube has reduced weight, allowing extended reach and improved fatigue life. An additional advantage resides in the fact that the coiled tube wall can contain and protect additional functional elements, such as electrical conductors and fiber optics for sensing and data communication.

Sensing systems based on Brillouin and Raman scattering can be used to verify the pipe operational parameters, prevent failure, optimize oil production from the well, provide strain distribution along the tubing and detect hot-spots in high-power cables. The integration of such sensing elements into composite tubing presents additional advantages and challenges. On one hand the embedded sensors are protected by the composite material and can be installed during production, avoiding external installation that could interfere with the tubing operations. In the other hand, the integration of optical fiber sensors into the composite structure requires the development of appropriate packaging and installation techniques that allow easy handling during production and avoid and damage to the sensor and the composite structure itself.

This contribution presents the sensing cable designs for temperature and strain sensing in a composite coiled tubing as well as testing results form initial field demonstrations.

6167-43, Session 9

High-resolution distributed sensor using dark Brillouin scattering

A. W. Brown, K. A. Brown, B. G. Colpitts, Univ. of New Brunswick (Canada)

Distributed sensors based on time-domain Brillouin scattering have typically had spatial resolutions in the metre range, with some advanced systems improving upon this by an order of magnitude. Resolution in the centimetre range generally has been made possible by using correlation based systems or frequency-domain approaches. Both of these techniques offer practical limits on overall sensing length and or acquisition speed. We present a new technique using dark pulses to implement a time-domain sensor system that provides centimetre resolution, with short acquisition times and minimal restrictions on sensing length. Results are shown to demonstrate the technique's efficacy in a number of applications.

6167-44, Session 10

Overview of fiber optic standarization activities

A. Méndez, MCH Engineering LLC

Optical Fiber sensors have reached a good level of maturity. They enjoy over 20 years of research and development. By now, there is a small but growing number of companies around the wrold offering a variety of fiber optic sensing products and systems.

A critical area to ensure a broader acceptance and use of this technology, as well as its compatibility across different suppliers and products is the formulation and adoption of standards.

In this paper, we present an overview of the ongoing activities related to standards on fiber optic sensors and their connection and relevance in regards to with smart structures and SHM. In particular, a discussion is made of the efforts carried out in the USA by the Fiber Optic Sensor Consortium within the Optoelectronics Development Association, NIST and others.

6167-45, Session 10

Guidelines and standards for fiber optic sensors: Quo vadis?

W. R. Habel, Bundesanstalt für Materialforschung und -prüfung (Germany)

Standardization activities for fiber optic sensor are increasingly discussed in the scientific as well as users community. Although numerous standards for fiber optic components have been available for years, guidelines or extensive standards for use of fiber optic sensors are still "in statu nascendi" and have to be developed. Standards for fiber optic sensors will be intrinsically very complex and thus different from standards for optical fibers, cable or connectors. They have to cover different functional physical mechanisms due to different physical principles for a multitude of measurands, application fields, and types.

The lecture will give first an overview on recent international, especially European activities in this field. It will propose second a possible classification for fiber optic sensor standards as well as a structure for guidelines needed for the most frequent practical applications. Special standardization issues to be pointed out for discussion will also concern:

- choice and design aspects for sensors for mechanical quantities (particularly strain and deformation)

- consideration of possible environmental and measurement-relevant circumstances on-site

- proof test conditions including validation procedure to evaluate and confirm sensor-related characteristics

- requirements on application techniques to bring the sensor system into service appropriately.

The discussion integrated in European and worldwide committee activities that already exist or will presently be started should cover all mentioned standardization aspects.

6167-46, Session 10

Reliability, availability, and maintainability considerations for fiber optical sensor applications

P. M. Nellen, R. Brönnimann, M. Held, EMPA (Switzerland)

ABSTRACT (invited)

Fiber optic sensors are potentially very well suited for condition monitoring of environment, materials, structures, and facilities. Measurable variables are mainly temperature, electrical current, strain and pressure. Optical fibers and sensors are often promoted to work in electromagnetic fields, at high temperature and humidity, or in aggressive chemical environment. Especially fiber Bragg grating (FBG) sensors have been demonstrated to operate in applications from airplanes to civil infrastructure like dams and bridges. However, there is a long way from a laboratory prototype to a reliable, standardized industrial sensor system. And there is an urgent need for a common understanding of terms.

As sensors have to be coupled to the monitored object, they are exposed to the environment in one or the other way. Either they have to be replaceable where the consistency of data has to be considered. Or, especially if replacement is not possible, they should outlast lifetime of the monitored objects, an optimized packaging and adequate protection is particularly important. Extensive aging and reliability tests are required to determine lifetime models and parameters for fibers, coatings, and sensors. Major factors influencing lifetime of fiber optic sensors are mechanical load from strain, bending or vibration, temperature, humidity, ice and water, chemicals, as well as dust and dirt. Reliability has to be considered during sensor system design, installation, and operating phase. Correctly built in redundancies increase data integrity and reliability considerably.

In this paper, based on the examples of fiber Bragg grating systems used for long term monitoring of strain and temperature, general sensor system reliability will be discussed. In addition, specific reliability considerations and lifetime tests, especially for relevant system components like optical fibers and Bragg gratings, coatings, and adhesives will be presented. A discussion of the advantages of redundant sensor structures and sensor systems RAM (reliability, availability, and maintainability) follows, applied to the critical non-repairable and non-replaceable sensor parts of two surveilled bridges. RAM considerations are the first steps towards standardized industrial sensor systems.

6167-47, Session 11

Application of long gage-length fiber optic sensors for monitoring pipeline integrity

R. C. Tennyson, D. Morison, Fiber Optic Systems Technology, Inc. (Canada)

This paper reviews the major pipeline structural integrity issues and how FT long gage-length fiber optic sensors (FOS)work.A structural health monitoring system is described, with reference to models that relate how to interpret the FOS measurements and correlate them with specific structural problems, such as corrosion wall thinning, bending and buckling for example.Details on actual installation techniques employed in the field are presented,along with problems that need to be addressed.Long-term reliability and system integrity criteria are described, with reference to different installations.A brief overview on the software requirements for data acquisition and management is given, with examples based on test data acquired from field sites.One of the major issues confronting the interpretation of sensor data is that of discriminating between “events”. In other words, how does one distinguish between a pipeline leak, and a buckled pipeline for example. What redundancy is required in sensor installations to differentiate false alarm signals from real events? This is a major concern in any structural health monitoring system installation.

6167-48, Session 11

Reliability and testing of distributed strain and temperature sensors

D. Inaudi, B. Glisic, Smartec SA (Switzerland)

Distributed fiber optic sensing presents unique features that have no match in conventional sensing techniques. The ability to measure temperatures and strain at thousands of points along a single fiber is particularly interesting for the monitoring of large structures such as pipelines, flow lines, oil wells, dams and dikes. Sensing systems based on Brillouin and Raman scattering have been used for example to detect pipeline leakages, verify pipeline operational parameters, prevent failure of pipelines installed in landslide areas, optimize oil production from wells and detect hot-spots in high-power cables.

The measurement instruments have been vastly improved in terms of spatial, temperature and strain resolution, distance range, measurement time, data processing and system cost. Analyzers for Brillouin and Raman scattering are now commercially available and offer reliable operation in field conditions.

New application opportunities have however demonstrated that the design and production of sensing cables is a critical element for the success of any distributed sensing instrumentation project. Although standard telecommunication cables can be effectively used for sensing ordinary temperatures, monitoring high and low temperatures or distributed strain present unique challenges that require specific cable designs.

This contribution presents three cable designs for high-temperature sensing, strain sensing and combined strain and temperature monitoring as well as the respective testing procedures during production and in the field.

6167-49, Session 11

Analysis of accuracy error and distortion in an operationally passive interferometric demodulation technique

M. D. Todd, Univ. of California/San Diego; J. M. Nichols, S. T. Trickey, M. E. Seaver, Naval Research Lab.

A system for interrogating fiber optic Bragg grating arrays at kiloHertz sampling rates with sub-microstrain resolution was presented recently. The system makes use of a tunable fiber Fabry-Perot filter for demultiplexing and a path-imbalanced Mach-Zehnder interferometer for wavelength conversion. The operationally-passive demodulation technique for the interferometer makes use of probing the 3x3 coupler at the interferometer output for its coupling parameters to execute the technique. In this work, we discuss the effects of how errors in determining these parameters translate into measurement error and harmonic distortion. We compare measured effects in the laboratory with predictive models to give error sensitivity metrics.

6167-50, Session 11

Sensor validation in nondestructive evaluation using the kernel-split method and clustering

V. Avasarala, The Pennsylvania State Univ.; J. Celaya, Rensselaer Polytechnic Institute; K. F. Goebel, N. Eklund, GE Global Research

Non-destructive evaluation (NDE) techniques for condition monitoring in remote solid structures have evolved vastly in the last few years. NDE techniques typically rely on multi-sensor data fusion, since the information provided by a single sensor may not be accurate or adequate to estimate system condition. However, sensor degradation and noise effects corrupt sensor information and adversely effect multi-sensor fusion. Algorithms for estimation of sensor integrity and for noise correction form a crucial aspect of NDE. This paper presents a sensor validation approach that verifies sensor integrity, identifies and corrects noise effects and selects the best possible array of sensors for multi-sensor fusion. This method has been developed for assessing sensor data obtained from a NDE field study that was used to differentiate between two types of defects, occurring in a solid structure. Multiple, heterogeneous NDT sensors were employed to examine the solid structure. However, features extracted from the time domain signals of these sensors had poor discrimination capabilities, due to noise effects that were caused by a) mal-functioning sensors and b) different constituents of the solid structures that produced sensor signals that dwarfed the signature of the defect. Therefore, a key challenge was to identify the best set of sensors among the heterogeneous sensors for use in the higher-level algorithms like feature extraction and pattern recognition. The sensor validation approach was used to a) remove noise effects and b) select the sensor with the best defect signature. The sensor validation approach used is as follows: Analysts marked areas of potential defects in the solid structure as “regions of interest”, using c-scan visualization that exhibits signal information from all the sensors. Rectification for noise was based on a specially devised algorithm called the kernel-split, which detects patterns across the region of interest and its adjoining areas, called as “context areas” in the solid structure. Kernel-split identifies patterns that do not show a significant change form the region-of-interest to the context and classifies them as noise. After noise correction, the sensor validation algorithm selects the sensor with the best defect signature. To that end, a clustering algorithm was used to detect and mark the signature of the defect in the region of interest. All sensors were ranked using a schema, based on cluster properties, such as cluster area, number of clusters etc. These ranks were used to select the best possible set of sensors that could be used for higher-level fusion, like pattern recognition. The results obtained using the sensor validation approach were compared to a manual sensor validation approach. The manual validation approach is highly time consuming. It involves human analysts viewing the signal data from all the sensors and manually selecting the best sensor. The outcome of the sensor validation approach and the manual selection approach coincided for a vast majority of the cases and vindicated the robustness of the present automated approach.

Conference 6168: Electroactive Polymer Actuators and Devices (EAPAD)

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6168-01, Session 1

What can we learn from nastic plant structures? The phytomimetic potentiality of nastic structures

R. Stahlberg, M. Taya, Univ. of Washington

While some researchers see developments on the nanotechnology scale as the major or exclusive biomimetic trend for the 21st century, others insist that the exploration of the biomimetic potentialities of macroscopic systems has hardly been started. On either scale, the exploration of biological systems and engineering materials will proceed in parallel and one can predict with certainty that the more these two processes are integrated, the greater will be the rewards for either discipline. Accordingly, recent studies of plant responses ranging from rapid calcium-dependent shape changes in proteins (forisomes) to the rapid closure of Venus flytraps and the ultra-rapid opening of dogwood flowers attracted the attention of a large audience of both biologists and engineers. In engineering, electroactive polymers have emerged as new actuation materials featuring large electrically induced strain and bending capacity. While dry EAPs are versatile tools, it is the wet or hydrated EAPs with low voltage-actuation may have relevance and proximity to biological situations; in particular nastic plant motors. Weak and strong electric fields were found to exist and change in plant and animal cells and tissues as well. Many aspects of their role, however, are unexplored and remain a matter of uncertainty and speculation.

6168-02, Session 1

Biologically inspired technology using electroactive polymers(EAP)

Y. Bar-Cohen, Jet Propulsion Lab.

Through evolution over billions of years nature introduced highly effective and power efficient biological mechanisms that are incredible inspiration for innovation. Humans have always made efforts to imitate nature and we are increasingly reaching levels of advancement that it becomes significantly easier to imitate, copy, and adapt biological methods, processes and systems. Advances in science and technology are leading to knowledge and capabilities that are multiplying every year. This brought us to the ability to create technology that is far beyond the simple mimicking of nature. Having better tools to understand and to implement nature's principles we are now equipped like never before to be inspired by nature and to employ our tools in far superior ways. Effectively, by bio-inspiration we can have a better view and value of nature capability while studying its models to learn what can be extracted, copied or adapted. Using electroactive polymers (EAP) as artificial muscles is adding an important element in the development of biologically inspired technologies. This paper reviews the various aspects of the field of biomimetics and the role that EAP play and the outlook for its evolution.

6168-03, Session 1

Designed chambered elastomers for enhancement of EAP actuation and applications thereof

D. F. Hanson, Hanson Robotics, Inc.

In this paper, the authors explore various ways that designed chambering of elastomers can enhance electroactive polymer (EAP) actuation. Such enhancements include structuring of chambers for various mechanical functions and advantages, boosting of surface area of a polymer for enhanced ionic migration, construction of advanced electret foams for sensing and for tunable hydrophobicity for micro/pumping action, and distribution of composite EAP devices throughout the chambered elastomer to achieve discrete controllability of electroactive polymer actuators.

With varied design of the chambers of the elastomer, the mechanical and structural properties of the elastomer can be tuned to greatly enhance EAP actuation. The chambers can be designed to act as one-way-valves for enhanced fluidic pumping, in accordion-like bellows to achieve extreme elongation with low forces, in chiral geometries to effectuate torsion under actuation, and as fluidic manifolds for fluidic sensing or tunable dampening and stiffness. These are but a few examples of the advantages that can be achieved via designed chambering of elastomers.

The authors also discuss the chambering of EAP materials themselves for enhanced actuation effects. Controlled hydrophobicity as a method for polymeric actuation is described. Enhanced ion exchange via chambering is also described.

The authors also discuss various application uses of the described chambering technologies. Such chambered elastomers, combined with advanced muscle-like actuators, can substantially benefit facelike robots (useful for entertainment and education etc), prosthetics, and numerous modalities of bio-inspired locomotion.

Methods for deploying chambering technologies with EAP actuators for useful applications are considered as well.

6168-04, Session 1

Design of commercial applications of EPAM technology

N. Bonwit, M. A. Rosenthal, J. R. Heim, C. Duncheon, A. Beavers, Artificial Muscle, Inc.

Since its inception in 2004, Artificial Muscle, Inc. (AMI), a spinout company from SRI International, has rigorously pursued the commercialization of artificial muscle technology that is called Electroactive Polymer Artificial Muscle (EPAM(r)) through innovative designs and fabrication processes and by focusing on performance, reliability and manufacturability across a wide variety of applications. Scaleable solutions developed by AMI include air and liquid pumps, valves, linear and angular positioners, sensors and generators. Innovative device designs demonstrating the ability to meet the specifications of demanding applications and combining practical levels of power densities and actuation lifetimes will be discussed. Integrated electronics control modules allow the freedom to design artificial muscles directly into new or existing product lines while effectively managing the transition from conventional technologies. Simple modular designs, coupled with low cost industrial materials and flexible automated manufacturing processes, provide a cost effective solution for products serving such diverse industries as consumer electronics, medical devices, and automobiles. Several case examples are presented to illustrate the commercial viability of EPAM(r)-based devices.

6168-05, Session 2

Arm-wrestling robot driven by dielectric elastomer actuators

G. M. Kovacs, EMPA (Switzerland)

On March 7, 2005, the first arm wrestling match of EAP robotic arm against human was held during the EAP-in-action session of the EAPAD conference in San Diego.

The Swiss Federal Laboratories for Materials Testing and Research (EMPA), Dubendorf, Switzerland, was one of the three participating organisations in this competition. The primary object was to demonstrate the potential of the EAP technology for such or similar applications.

Dielectric acrylic elastomers are well-known as materials for electric field-induced actuators. Thereby, the thin elastomer film is sandwiched between two compliant electrodes. When a large electrostatic field is applied to the electrodes, the elastomer is squeezed in thickness direction and elongates thus in planar directions. The investigation of various actuator designs has shown that very promising actuation performances are reached when a pre-stretched dielectric elastomer film is wrapped around a flexible core.

The arm robot developed at Empa was driven by a system of such dielectric elastomer actuators. More than 250 rolled actuators were arranged in two groups according to the human protagonist-antagonist operating principle in order to achieve an arm-like rotation movement in both directions and to accomplished the basic arm wrestling competition rules: the active movement from the horizontal arm position to the upright starting position and the reverse "arm wrestling motion" exhibiting maximal force. The robot was powered by a computer-controlled high voltage device. The rotary motions of the arm were controlled by electrically activating respectively deactivating the corresponding actuator group.

The focus of this talk is on the development and manufacturing technique of the rolled dielectric elastomer actuators and on the engineering procedure for the robot design. In addition, the major issues concerning the overall efficiency and long term behaviour of rolled dielectric elastomer actuators are presented. Finally, the signification of the EAP technology for future applications will be discussed in the scope of "lessons learned".

6168-06, Session 2

New high-performance electroelastomers based on interpenetrating polymer networks

Q. Pei, S. M. Ha, W. Yuan, Univ. of California/Los Angeles; R. Pelrine, SRI International

We will present our recent development of a new class of electroelastomers operating at zero to minimal prestrain. The new electroelastomers are composed of interpenetrating polymer networks in which one network is under tension while the other under stress. The polymer films exhibit electrically induced strain greater than 200%. These new electroelastomers promise new actuators that contain minimal prestrain-supporting structure and are more compliant. The packaged actuator will also have higher energy and power densities when compared to our previously reported electroelastomer (a.k.a. dielectric elastomer) actuators.

6168-07, Session 2

Breakdown field improvement in silicone dielectric polymers via compression molding

R. Chakraborty, Massachusetts Institute of Technology

The strong dependency of electroactive polymers on prestrain is a significant drawback as an actuator. Prestraining plays an important role in generating large strain by increasing the breakdown field of the elastomer. However, the elastic forces by prestrain makes the deformation smaller, and the induced stress relaxation is severely detrimental as an actuator.

It has been suggested that elastomer chains are more resistant to breakdown when they lie perpendicular to an electric field than when they lie parallel to it, and that this effect may account for the performance improvements observed with prestraining. The research proposes an alternative method, compression molding, to produce some degree of alignment in the polymers to increase breakdown field.

Compression molding consists of two metal plates separated by a 50um thick tape. The silicone tested (NuSil CF-19-2186) is available in a two-part system with a working time of 10 minutes. The mixed substance was placed between the plates and compressed to a 50um film. The forced radial shear flow is believed to induce the elastomer chains to align parallel to the plates. The mold was compressed with platens in a vacuum (190psi) at variable temperature to determine the effect of curing time on breakdown field. The cured silicone was then tested using silver grease electrodes.

In preliminary tests, silicone manufactured by an extrusion casting system without prestrain and with prestrain showed breakdown fields less than 30 V/um. Silicone manufactured through the compression molding procedure showed a threefold improvement in breakdown field, withstanding up to 125 V/um. The average breakdown field also increased with curing temperature. This is consistent with the hypothesized induced alignment in that fast-curing silicone chains would have little time to randomize before reaching its final cured state.

Future tests will include density measurements of the compression molded silicone through refractometry. This technique would gauge the degree of order in the elastomer chains.

6168-08, Session 2

Cylindrical dielectric elastomer actuators reinforced with inextensible cords

N. C. Goulbourne, Virginia Polytechnic Institute and State Univ.

Novel actuator configurations for various applications can be obtained using cylindrical dielectric elastomer actuators. Cylindrical dielectric elastomer actuators simultaneously deform in the radial and axial directions when a voltage is applied in the thickness direction. Although dielectric elastomer actuators are capable of very large strains, the force generated during actuation is very low. To increase the force output of dielectric elastomer actuators, the elastomer is reinforced by inextensible cords with a higher modulus of elasticity. This confers added strength to the composite elastomer. As a direct result of the inextensible cords, deformations are reduced along the path of the cords. An electroelastic numerical model is used to predict the large deformation behavior of the actuator. The model combines Maxwell-Faraday electrostatics and nonlinear elasticity. Two specific configurations are examined in this work: (1) uniform actuation and (2) segmented actuation. During uniform actuation the deformation is cylindrically symmetric. On the other hand, during segmented actuation the resultant motion of the actuator is non-uniform since portions of the cylinder are independently actuated. In this paper, numerical results and experimental results are compared.

6168-10, Session 3

Highly aligned electrostrictive graft elastomer nanofibrils and electromechanical activity

J. Su, P. T. Lillehei, NASA Langley Research Ctr.; T. Xu, National Institute of Aerospace

Electroactive polymers (EAPs) have been considered as one of the most promising materials for artificial muscle applications. The electrostrictive graft elastomer, developed at NASA, is one of the newly developed electromechanically active polymers that can be used for artificial muscles. This graft elastomer demonstrates a large electrical field-induced strain and high mechanical modulus. The unique mechanism of the electromechanical properties of the graft elastomer allows for an increase in both the field-induced strain and the mechanical modulus at the same time by using morphology control. Therefore, high electromechanical power, which is determined by the strain and the modulus, can be generated. Recently, a novel method was developed to create highly-aligned nano-fibrils of the graft elastomer. The characterization of the fibrils using scanning electron microscopy (SEM) and atomic force microscopy (AFM) demonstrated that the fibrils are round-shaped with a diameter of 70-160 nm and are uni-axially aligned in the fibrils' axial direction. The test of the electromechanical response of the fibrils showed that the electrical field-induced strain of the highly aligned fibrils is very similar to the strain demonstrated by the film form of the graft elastomer. These results make highly-aligned nano-fibrils of the electrostrictive graft elastomer a promising candidate for artificial muscle applications.

6168-11, Session 3

Contractile dielectric elastomer actuator with folded shape

F. Carpi, D. De Rossi, Univ. di Pisa (Italy)

Linear dielectric elastomer actuators with contractile ability are demanded today for several types of applications. In order to achieve such a goal, two basic actuating configurations are today available: the multilayer stack and the helical structure. The first one consists of several layers of elementary planar actuators stacked in mechanical series and electrical parallel. The second one relies on a couple of helical compliant electrodes alternated to a couple of helical dielectrics. The fabrication of both these configurations presents today some specific difficulties, arising from the peculiarity of each structure. Even though successful implementations have been reported and further improvements are currently in progress, the availability of simpler solutions would boost the short-term use of contractile actuators in practical applications. In order to propose a viable alternative to the present configurations, a new structure is here described. It is designed to obtain a contractile monolithic actuator, starting from a planar electroded sheet, which is then folded up. The resulting compact structure is equivalent to a multilayer stack with interdigited electrodes and square cross-section. With respect to the conventional multilayer stack, the new configuration is advantageously not discontinuous and can be manufactured in one single phase, avoiding layer-by-layer multistep procedures. The current developmental stage of this new actuator with a silicone elastomer is here presented.

6168-12, Session 3

Modeling of silicone dielectric elastomer actuators

G. Akhras, Royal Military College of Canada (Canada); G. Yang, EXFO (Canada); B. K. Mukherjee, Royal Military College of Canada (Canada)

Dielectric elastomers are known to produce large transverse strains in response to electrically induced Maxwell stresses and thus provide a useful form of electromechanical actuation. Using an interferometer, experimental results show that a pre-load initially causes an increase in the strain. This increase appears to be a function of the relative geometries of the electroded area and of the specimen itself. The transverse strains in these materials decrease when larger values of pre-load are applied. Models of hyperelasticity capable of describing large deformation of rubber like polymers are used to describe and interpret the results. Numerical simulations of the material's behaviour are performed in order to provide an accurate prediction of the actuator's performance.

6168-13, Session 3

Electromechanical model for static and dynamic activation of elementary dielectric elastomer actuators

P. Lochmatter, S. Michel, G. Kovacs, EMPA (Switzerland)

In this paper the fundamental static and dynamic electromechanical behavior of Dielectric Elastomer (DE) actuators under activation is investigated. In the static case, the dielectric film was modeled with a simple three-dimensionally coupled elastic material model. This model was fitted to the mechanical stress-strain be-

havior of the well-known dielectric film VHB 4910 (3M) evaluated in a uniaxial tensile test. The model predicted in all cases stable deformation states for activation under constant electrical charge. For activation under constant electrical voltage however, the model predicted two equilibrium states - a "stable" and an "instable" one. For activation voltages beyond a "critical voltage" the film collapses in thickness direction due to the electrostatic forces (Maxwell stresses). The mechanical energy density and the global electromechanical efficiency of such DE actuators under closed quasi-static activation loops were derived. The model showed strongly improving actuator performance for activation voltages close to the "critical voltage".

For the investigation of the dynamic electromechanical behavior of DE actuators, the model was enhanced by two parts: first, the incorporation of dampers into the mechanical model to cover the film's viscoelasticity and second the embedding of the actuator into an appropriate electrical circuit. The viscoelastic model parameters were fitted to a typical combination of a uniaxial loading test with holding time and subsequent unloading.

This electromechanical model was evaluated in terms of closed loop activation cycles of a one-dimensionally pre-strained stripe actuator. The stripe actuator was either cyclically actuated and cyclically loaded with a phase shifted external force ("force-controlled") or cyclically actuated and cyclically elongated with a phase shift ("displacement-controlled"). A qualitative parameter study showed that the global electromechanical efficiency as well as the specific energy density of such DE actuators strongly depends on the mechanical properties of the film, the electrical activation level and the external mechanical loading.

6168-14, Session 3

Polymer models: compilation and modeling in computer simulation

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The work focuses on computational study of PTFE polymer chain. PTFE models are particularly interesting because of applicability as Nafion backbone. The main purpose of this work was to find proper force field and modeling strategies for aforementioned Nafion backbone chain. Force fields by Jang and Borodin were compared in Monte Carlo chain generation and Molecular Dynamics simulations. Polymer chains consisting of 180 to 200 monomers were generated and studied. These chains were approximately 10 times longer than in previous analysis, where ultimately 20 units long oligomers were investigated. After overcoming several problems, simulations were performed with Jang's and Borodin's force fields. Analysis of densities, infrared spectra, radial distribution functions and dihedral distributions were conducted. The following results were obtained: for amorphous phase of PTFE force field indicated relatively close and slightly smaller densities than experimental ones. Infrared spectra qualitatively reproduced experimental results. Also RDF copied previous results which were in good agreement with static structure factor and X-ray scattering studies. Helical conformation, like expected, was noticed, but it was smaller (10º) than experimental studies have had proved (14º). Despite of missing crystallinity in particular studies, strongly prevailing trans-conformation peak in dihedral distribution was observed, which should support formation of crystals. In particular case the simulation box was too small and time of the simulation was too short to make crystal formation possible. The main advantage of Borodin's force field was stability with longer time steps. As a conclusion it might be said that both force field had relatively equal performance and preference of force field should be based on additional studies in particularly interesting conditions.

6168-15, Session 3

Finite element and experimental analysis of non-axisymmetric

E. Yang, M. I. Frecker, E. M. Mockensturm, The Pennsylvania State Univ.

In this paper the general-purpose finite element software ABAQUS is used to model the viscoelastic response of non-axisymmetric dielectric elastomer membrane actuators. Geometries investigated consist of membranes with holes in the shape of an ellipse, rectangle, and a square. ABAQUS is used to calculate the deformation and block force fields on the surface of each membrane. These results are used to aide in the selection of actuator configurations that yield the largest deformation and block force fields. The actuators are fabricated and experimentally analyzed using the particle image velocimetry technique commonly used in the study of fluid flow. The 3M VHB polyacrylate and silicone dielectric elastomer materials are utilized in this research.

6168-16, Session 3

Integrated theoretical model of EPAM technology

A. Beavers, Artificial Muscle, Inc.

Over the last few years, there have been several papers published which form the basis of the theory behind electroactive polymers in general and dielectric elastomers in particular. In most cases, these papers focused on salient but relatively narrow aspects of the field of electroactive technology. Presented in this paper is an integration of these essential theoretical elements with the objective of forming a basis for a comprehensive understanding and comparison of the most promising forms of electroactive polymer technologies. Included in this paper will be a model that captures the relationship and interdependence of elasticity and capacitor theory, polymer chemistry, power electronics, and mechanical dynamics as they relate to the application and evaluation of electroactive polymer technologies. This theoretical analysis has evolved out of the efforts of Artificial Muscle, Inc., a young company founded in 2004 as a spin-out of SRI International for the purpose of commercializing a form of electroactive polymer technology that has been named Electroactive Polymer Artificial Muscle (EPAM(r)). The integrated theory will be used in this paper to compare and contrast three different types of electroactive polymer technology.

6168-17, Session 3

The role of multifield theories in the modeling of active materials

M. Gei, Univ. degli Studi di Trento (Italy); P. M. Mariano, Univ. degli Studi di Roma/La Sapienza (Italy); L. Magnarelli, Univ. degli Studi di Trento (Italy)

The theoretical prediction of the experimental observations in the field of 'active materials' requires the formulation of specific models which depend on the nature of the driving mechanism of that specific phenomenon. An extremely limited list of such phenomena are piezoelectricity and electrostriction, where strain is induced by an electric field, ionic transport in chemically-activated materials, liquid crystals. Even though such examples seem not to share any feature, in all of them the material displays activity at the microstructural level. We call 'complex' such materials, when their substructure from nano to meso-level influences drastically their gross behaviour in a way in which interactions due to substructural changes are prominent and cannot be smeared out as in common homogenization procedures. There exists a general model building framework (the one of 'multifield theories') that unifies common models of complex materials and is also a theoretical tool to construct new special models for the behaviour of new complex materials produced in the industrial practice. Such a framework is essentially the geometry and the mechanics associated with maps between manifolds. In the standard format of continuum mechanics a body is a set of material elements whose morphology is identified just by their place in space. In this way, the geometrical description of the body skips details about the minute substructure.

However, when one looks to real bodies, one realizes that the material elements is not properly just a material point, but, rather, a system of interacting molecules. To describe the morphology of this system a 'morphological descriptor' (order parameter) is introduced. It may be an element of the unit sphere, a stretchable vector, a second-order tensor of various nature, etc., depending on the physical conditions envisaged. Of course, we could develop models for each choice of the order parameter to describe different physical situations. Formally, all of them arise from the same general model-building framework, the one of multifield theories.

To construct the formal structure of models of complex bodies we need just to require that morphological descriptor be an element of an abstract manifold M of substructural shapes, endowed with 'minimal' geometrical properties.

The choice of M is the first step toward the construction of each special model, thus it has a 'constitutive' nature, in a sense wider than usual. The introduction of morphological descriptors - to represent details of the morphology of the body - allows to account directly for interactions due to substructural events that may change, even drastically, stress distributions. In fact, interactions within a body are objects conjugated in the sense of power with the rates of its morphological descriptors. Here these rates are the standard velocity and the rate of change of the order parameter. Standard tensions are associated with the former while micro-tensions with the latter. A new balance arises: the local balance of substructural interactions. In the context of electric EAP the polarization vector is a typical example of order parameter. The microstress associated with rate-of-change of polarization gradient is responsible, for instance, of domain switching in ferroelectrics.

Another important class is that of ionic EAP, where the morphological descriptor may be a scalar quantity representing the ion concentration.

6168-18, Session 4

Possibility of cellulose electro-active papers as smart materials

J. Kim, Inha Univ. (South Korea)

With technological interests in renewable raw materials and more environmentally friendly and sustainable resources, a renaissance of cellulose research and application has been triggered over the past ten years. This paper will present a recent discovery of cellulose papers as smart materials that can be used for bio-mimetic sensor/actuator devices and microelectro-mechanical systems (MEMS). This cellulose paper is termed as Electro-Active paper (EAPap). First, the discovery story of EAPap as an actuation material is addressed along with fabrication and recent improvement of EAPap materials. The actuation mechanism is also explained by gathering all information on physical, chemical, electrical and mechanical observations. Also the functional capability of sensor/actuator is discussed with experimental testimony. The cellulose EAPap materials have merits in terms of ultra-lightweight, dryness, low cost, low actuation voltage, low power consumption and biodegradability. To demonstrate these advantages, applications such as micro insect robots, micro flying objects, MEMS, biosensors and flexible electrical displays are discussed with some examples. Dealing with ultra-lightweight actuation devices, a remotely driving technology is important. Thus, microwave driving technology is introduced with biomimetic devices. In summary, possibility of cellulose papers as smart materials will be addressed with the future direction and challenges in this research.

6168-19, Session 4

Electro-active paper made with aqueous and non-aqueous cellulose solution

N. Wang, J. Kim, Y. Chen, S. Bae, S. Lee, Inha Univ. (South Korea)

Electro-Active Paper (EAPap) is attractive for EAP actuator due to its merits in terms of lightweight, dry condition, large displacement output, low actuation voltage and low power consumption. EAPap actuator has been developed based on cellulose material. Cellulose fibers are dissolved into a solution and extruded in a sheet form, and a thin gold electrodes are made on it. The cellulose solution has been made according to the viscous process that uses aqueous solvent NaOH and non-aqueous method (DMAC / LiCl). The use of strong alkali aqueous solvent or DMAC / LiCl results in decreasing hydrogen-bond of cellulose molecules. It makes EAPap material possessing ionic behavior to mix with anionic polymer in solution. On the other hand, cellulose were added conducting polymer (such as polyaniline or polypyrrole) or PZT (Pb(Zr,Ti)O3) has piezoelectricity. Thus, it is necessary to maximize the piezoelectric effect by adding some other material. The cellulose solution in aqueous sodium hydroxide show the common viscoelastic behavior at about room temperature, in coagulating solvent the cellulose solution become cellulose III crystal. The cellulose III crystal show some degree piezoelectric property. Performance of EAPap actuator made by non-aqueous solvent is compared with the previous EAPap material in terms of force and displacement along with frequency, voltage, temperature and humidity.

6168-20, Session 4

Electromechanical properties of LaRC EAP: a SWNT-polyimide nanocomposite

J. S. Harrison, S. E. Lowther, N. M. Holloway, NASA Langley Research Ctr.; J. Kang, C. Park, National Institute of Aerospace

Much has been said about the electrical and mechanical properties of carbon nanotubes and carbon nanotube-polymer composites. However reports of the electromechanical properties of these materials are scarce. Herein we report the electromechanical properties of a novel series of single wall carbon nanotube (SWNT) -polyimide nanocomposites (LaRC EAP). Small loadings of SWNT were incorporated into an amorphous, piezoelectric polyimide, a nitrile-substituted APB/ODPA. These nanocomposites exhibit both a sensing and an actuation response. Sensing properties of LaRC EAP were explored as a function of stress, strain, pressure, and temperature. Out-of-plane strains as large as 2.6% were measured at relatively low field strengths (< 1 MV/m) and cantilever-like bending strains in the similar range were measured at equally low fields. This presentation will highlight the electroactive sensor and actuation characteristics of LaRC EAP and explore potential aerospace applications of these materials.

6168-21, Session 4

Development of new synthetic rubber for energy efficient polymer actuators

H. R. Choi, J. Koo, K. Jung, M. Jung, J. Nam, Y. Lee, Sungkyunkwan Univ. (South Korea)

Dielectric elastomers are one of the most actively studied EAP materials for new generation of actuators. Although many different dielectric elastomers have been developed and used for the implementation of various new actuation concepts, effectiveness of the newly introduced actuator design is often limited by the mechanical characteristics of the elastomer. Those characteristics are time dependent stress relaxation, low actuation force, and limited tensile strength. The present paper introduces a new synthetic rubber based dielectric elastomer that provides higher dielectric constant, stronger tensile strength, and less stress relaxation compared with the existing material.

6168-22, Session 5

Study on actuating mode shapes of electroactive paper

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The paper presents a study on actuating mode shapes of cellulose-based Electro-Active Paper (EAPap) in order to investigate its suitability as actuators. As well known, the cellulose is almost inexhaustible source of raw material for increasingly demand for environmental and biocompatible products as an important skeletal component in paper and also has hydroxyl groups, which are responsible for water sorption to participate in hydrogen bond. Cellulose with crystalline structures upon the electric field is ionically conducting materials, in which their conductivity is very sensitivity to the relative humidity and is related with the mobility of ions. Especially in aqueous environments, the hydrogen of water molecular may jump to a nearby water molecule under electric fields. The water molecule losing its hydrogen becomes negatively charged as a “hydroxyl ion (OH-)” and the water molecules gaining the hydrogen becomes positively charged as a “hydronium ion (H3O+)”, which replaces alkali metal ions such as and in the view of electrolytes. According to magnitude and direction of electric fields, the migration of these ions can produce a suitable deformation of the cellulose-based paper, which gives an actuating capability with light weight, low power consumption and simple fabrication. On the other hand, the cellulose coated with electrodes acts as a dielectric component in condenser. Dielectric property of the cellulose greatly related to dipole moment increases with respect to water molecules, which gives an effect on the longitudinal direction of cellulose as an actuating component. Herein, EAPap is fabricated by embedding gold as electrodes into both sides of cellophane sheets. The cellophane has a higher dielectric constant and a lower degree of polymerization. Stiffness of gold electrodes coated through physical vapor deposition is negligible compared to that of the host cellophane material. The size of EAPap is long 40mm and 10mm wide with thickness of 20umm. Phenomenological characteristics of EAPap are evaluated by applying electric fields at different exciting frequencies as well as different humidity. Actuating mode shapes upon applying electric fields are experimentally evaluated via laser scanning vibrometer as a function of frequency and humidity. Furthermore, a theoretical model based on the micro mechanism of ion migration and dipole moment is suggested to predict a macro point of view on actuating effect. The modeling is incorporated with electrostatic and hydraulic effects, along with dipole moment of water molecules. Through the comparisons between the experimental and theoretical results, the proposed modeling and the actuating mechanism are adopted to represent EAPap-based smart structures. The results obtained from the proposed methodology indicate that EAPap can be used as a potential actuating candidate for shape control of smart structures, along with bio-inspired actuator materials.

6168-23, Session 5

Reliability of high-strain ionomeric polymer transducers fabricated using the novel direct assembly process

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Ionomeric polymer transducers have received considerable attention in the past several years. These actuators, sometimes referred to as artificial muscles, have the ability to generate large bending strain and moderate stress at low applied voltages.

Typically, ionic polymer actuators are composed of Nafion-117 membranes with platinum electrodes and are saturated with water diluents. Recently the authors have developed a novel fabrication technique named the Direct Assembly Process (DAP), which allowed good control on electrode morphology and composi-

tion. The DAP consists of spraying two high surface area metal-ionomer electrodes on a Nafion membrane. A single-walled carbon nanotubes (SWNT) and ruthenium dioxide (RuO2) hybrid electrode was sprayed on a Formamide hydrated Nafion-117 membrane using the DAP method. This transducer was shown to generate 9.4% peak-peak strain under the application of +/-2V at a strain rate of 1%/sec. Furthermore using the DAP one is capable of incorporating several types of diluents in ionomeric polymer transducers. Transducers with ionic liquid diluents are demonstrated to operate in air for long periods of time.

In this work we will present a reliability study of transducers fabricated using the DAP. Each transducer is tested under a frequency range of 0.2Hz to 1Hz, and a potential of +/-1V to +/-3V. Water hydrated transducers dehydrates and stop moving within 5 minutes while operating in air under +/-2V. Transducers with Formamide diluents operate for 20,000 cycles under +/-1.5V and 0.5Hz (around 11hrs), while they degrade in less than 3000 cycles under +/-2V and 0.5Hz. Ionic liquid based transducers are demonstrated to operate in air for over 400,000 with little loss in performance. Actuators with several electrode compositions are fabricated and a correlation between the reliability of ionic liquid-ionic polymer transducers and maximum strain will be presented. This correlation will be used to asses the adhesion between the high surface area electrodes and the Nafion membrane. SEM images of tested transducers will be presented. Degradation mechanism will be characterized.

6168-24, Session 5

Nanomesa and nanowell formations in Langmuir-Boldgett polyvinylidene fluoride trifluoroethelyne copolymer films

J. Li, Univ. of Nebraska/Lincoln

Self-organizing nanomesa and nanowell patterns have been observed in Langmuir-Blodgett (LB) films of polyvinylidene fluoride trifluoroethelyne [P(VDF-TrFE)] copolymers recently. In this talk, we report an energetics-based model combined with kinetic relations to explain this remarkable phenomenon. One of the key assumptions of our model is that the internal energy density of P(VDF-TrFE) films varies with the surface concentration of molecules, reflecting its dependence on the morphology of polymer chains. The feature size of nanomesas and nanowells has been estimated using a linear stability analysis, and the morphology of the nanomesas and nanowells has been revealed by the numerical simulation, both in consistency with experiments. A number of other model predictions regarding the nanomesa and nanowell formations also agree with experimental observations. The nanomesas and nanowells can be used as template to fabricate electroactive nanocomposites.

6168-25, Session 5

Flemion-based actuator with ionic liquid as solvent

J. Wang, C. Xu, Univ. of Washington

A perfluorinated carboxylic acid membrane, i.e. Flemion, shows improved performance as actuator material compared with Nafion (perfluorinated sulfonic acide). Flemion has a higher ion exchange capacity and good mechanical strength. Especially, Flemion will deform with no back-relaxation when applied electrical stimulus. However, with water as solvent, the operation of Flemion in air has serious problems. Since water would evaporate quickly in air. Moreover, the electrochemical stability window of water is less than 1.4V at room temperatures. In previous work, investigations on Nafion with ionic liquid as solvents have been carried out and good results have been obtained. In current work, we explore the use of highly stable ionic liquid instead of water as solvent in Flemion. Experimental results indicate that Flemion based actuators with ionic liquid as solvent have improved stability as compared to the water samples. However, the forces that Flemion based actuators with the use of ionic liquid output decreased dramatically as compared to water. These initial results still suggest good potential for this approach in future work. An antenna switch actuator based on Flemion with ionic liquid will be discussed in this study.

6168-66, Poster Session

A method to estimate the deformation and the absorbed current of an IPMC actuator

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Basing on the work presented in the last EAPAD Conference and supported by the European Community by the research project ISAMCO (Ionic polymer metal composite as Sensors and Actuators for Motion COntrol, 2004-2006) inside the sixth Framework Program, the proposed paper goes on describing the results about the characterization of IPMC materials as motion actuators, obtained by using an improved infrared-based system designed, realized and characterised to this aim. The system was asked to detect both the IPMC absorbed current and its consequent deflection, under the effect of the applied voltage. The deflection is detected by the IR system, that uses a differential configuration in order to reduce non-linearity, peculiar to IR devices. This system is able to detect displacement from tenth of millimeters to few centimeters, in a frequency range from hundreds of millihertz to hundreds of Hertz, that is compatible with the IPMC actuator bandwidth, with the specification of low cost. The measurement system that we developed is use to identify and then validate a model, proposed to analytically describe the IPMC actuator behaviour in a wide range of operating conditions. The model was synthesised by adopting a grey box approach. The two quantities, detected by the measurement system, that are current and deflection, are considered respectively as input and as output of the electro-mechanical block model of the actuator, and are necessary to identify the parameters of the model, in order to estimate its behaviour. The electromechanical stage follows an electrical stage that transduces the applied voltage into the absorbed current: this block counts for the non linear phenomena referred in the literature and experimentally evident. By acquiring the signals involved: the applied voltage, the absorbed current and the IPMC displacement, for different inputs such as pulses, sinusoidal waves (varying frequency and amplitude) and noise, and by post processing these signals, all the parameters relative to the IPMC actuator were identified and several tests were performed in order to compare the behaviour of the actuator as predicted by the model with the experimental one. The obtained results show a very good accordance between the simulated and the real actuator response, hence represent a good validation of the proposed model.

6168-67, Poster Session

A multiphysics model of ionic polymer-metal composite actuator

D. Kim, K. Kim, Univ. of Nevada/Reno

Ionic Polymer-Metal Composite (IPMC) is a promising smart material for future use in biomimetics, robotics, and mechatronics. In order to better understand the electro-chemo-mechanical behavior of IPMC, we developed a mathematical model which deals with multi-physics tasks including mechanical, electrical, and chemical phenomena, simultaneously. In this study, the multiphysics of interest consists of force generation, electrostatics, momentum, heat and mass transfer, and electrochemical reactions. The physical phenomena of the studied system are described as coupled partial differential equations. Also, model experiments were conducted to obtain important model parameters. The proposed model was then implemented in the FEMLAB and MATLAB platform. The model results were compared against experimental data. Seemingly, the model accurately predicts the non linear behavior IPMCs.

6168-68, Poster Session

Sensory behavior of ionic polymer metal composite

A. Pudipeddi, K. Kim, D. Kim, Univ. of Nevada/Reno

Ionic Polymer-Metal composite (IPMC) sensory systems have been intensively investigated due to their unique properties such as softness, light weight and flexibility. The systems can convert inner reaction energy to electrical signal under applied force. Electromechanical sensors and actuator systems are largely used in medical, electronic and industrial applications. This work is based on the doctrine that there is a production of charge on the surface of the IPMC under a mechanical deformation. Various experiments were conducted on IPMCs with different solvents, electrode materials, thickness and aspect ratios and studied in both time and frequency domain. The results show that the ionic liquids as solvents gave more regular and stable response for sensing when compared to the aqueous medium. The polypyrrole coating in aqueous medium gave a consistent response when compared to platinum IPMC. In this presentation mechanical characteristics of the IPMC are also presented.

6168-69, Poster Session

Thermal management of ionic polymer-metal composites

S. Vemuri, K. Kim, Univ. of Nevada/Reno

The main objective of the current research work is to theoretically evaluate 2-D transient temperature distribution in an IPMC. Most of the prior work on IPMC concentrated on its ability as an actuator. The effect of temperature distribution due to applied voltage in an IPMC composite has not been studied earlier and is the main subject of the current research. In determining the temperature distribution in IPMC, FEMLAB software was used for modeling purpose. In developing the model the IPMC is assumed to be at room temperature. Surrounding air temperature and convection due to air are considered in developing the model. Equal amount of heat flux was applied at the electrodes. In developing the model platinum and Nafion are assumed to be in perfect thermal contact. The data obtained

form the model showed that a maximum temperature rise was seen at the regions where the heat flux was applied and the rest of the IPMC has shown no significant rise in temperature. This may has been attributed to Nafion's very poor thermal conductivity and very high specific heat capacity. The effect of varying external surrounding air heat transfer coefficient form 1 to 100 W/m2-K was also studied on the maximum temperature rise in the IPMC.

6168-70, Poster Session

Muscle-like linear actuator by using ionic polymer-metal composite and its actuation characteristics

S. Lee, K. Kim, Univ. of Nevada/Reno

IPMC (Ionic Polymer-Metal Composite) actuators produce large bending behaviors under low input voltages and are flexible enough to be potentially implemented in biomedical applications. Realizing that natural muscles generate strain and stress via linear actuation, the bending behavior of IPMC actuator needs to be converted to linear motion for mimicking natural muscle-behavior. In this study, IPMC was used for developing muscle-like linear actuator. In the design process, numerical analysis was utilized to predict free strain and blocked stress of IPMC-made linear actuators. Large free strain and blocked stress are the most important factors for the development of artificial muscle. Based on the preliminary analysis results, an effective linear actuator was successfully fabricated by using IPMC components. In order to evaluate the performance of the manufactured linear actuator, actuation displacement and force were measured. The measured data showed a good correlation with the estimated results.

6168-71, Poster Session

Silkworm protein: its possibility as an actuator

H. Jin, S. J. Myung, H. S. Kim, W. Jung, J. Kim, Inha Univ. (South Korea)

In the last ten years, Electro-active polymers (EAP) have received much attention as a result of the development of new EAP materials that exhibits a large displacement. This characteristic is a valuable attribute that has enabled a myriad of potential applications, and it has evolved to offer operational similarity to biological muscles. The potential to operate biologically inspired mechanism driven by EAP will offer capabilities that are currently considered science fiction. EAP are able to offer a range of performance and characteristics that may not be reproduced by other technologies. Therefore, it is certain that EAP materials have, indeed, a promising future for applications as such biologically inspired actuators thus driving various mechanisms for manipulation and mobility including microrobots, micro flying objects and animatronic devices. Recently, silkworm protein received attention as a possible biologically inspired actuator.

In this paper, the possibility of silkworm protein as an actuator will be examined. Silk films will be prepared from high concentrations of regenerated fibroin in aqueous solution (~8 wt%). Films with thicknesses that ranged 100 to 150 mm will be prepared for coating electrodes. These cast films will be annealed in water at room temperature to induce formation of a silk I structure. After that, silkworm protein actuator will be made by constructing thin gold electrodes on both sides of the film. When electrical voltage is applied on the electrodes, the silkworm protein actuator produces bending displacement. Therefore, this paper will describe the working principle and performance of silkworm protein actuator as an artificial muscle and its possibility for many applications.

6168-72, Poster Session

Manufacturing and characterization of ionic polymer metal composites with silver as electrodes

S. D. Pandita, H. T. Lim, Y. T. Yoo, H. C. Park, Konkuk Univ. (South Korea)

In the past decades, ionic polymer metal composites IPMCs have gained a great deal of interests as actuators and transducers. IPMCs can exhibit large dynamic deformation under a time varying electric field. The properties of IPMCs are affected by many factors such as cations, solvents, and electrodes. The most widely used electrodes for IPMCs are platinum metals. At present, non precious metals such as silver and copper are used only as the secondary electrode. Copper was employed in the secondary depositing or co-reduction process in order to reduce the production cost. As a secondary electrode, copper is less likely to contact with solvent and reactive sulfuric groups in Nafion. The use of silver metals as primary electrodes for IPMC has not yet been reported. Tollen's reagent that contains silver cations can be easily synthesized and economically feasible compared with gold and platinum compounds. Based on the electrochemical oxidation potential, the nobility of silver is in between copper and gold. The electrical conductivity of silver is the best among gold, copper and platinum. However, silver metal can be easily dissolved or oxidized in hot concentrated sulfuric acid solution. Silver can also be dissolved in dilute or concentrate nitric acid solution. In this research, silver metal is investigated as primary electrodes for IPMCs. Silver is deposited on Nafion 117(r) by using sodium boron tetrahydrate as the reduction agent. Silver IPMCs show higher conductivity than Platinum IPMCs. The thickness of the silver electrode from both initial compositing and surface electroding processes is about 40 microns, which is thicker than the common platinum electrode (about 20 microns). The high conductivity of silver IPMCs certainly gives better the actuation response. Two types of solvents will be investigated in this research, namely electrolyte (Li+) solution and ionic liquids.

6168-73, Poster Session

Multiwall carbon nanotube mixed EAPap material for smart materials

C. Song, S. Yun, S. Bae, N. Wang, J. Kim, Inha Univ. (South Korea)

The paper will present a new Electro-Active Paper (EAPap) made by mixing multiwall carbon nanotubes (MWNT) with cellulose solution. EAPap material is attractive as smart materials due to its merits in terms of lightweight, dry condition, large displacement output, low actuation voltage, low power consumption and biodegradability. However, there are some challenges in EAPap research: force output and frequency band should be improved. For the sake of this, MWNT is mixed in the cellulose EAPap material. This approach will enhance not only the mechanical property but also the electrical property of EAPap material. Cellulose solutions are made with aqueous and non-aqueous solvents, and MWNT are mixed in them by sonicating. The mixed solutions are cast into a sheet form by means of spin coating, dip coating and extrusion as well. Physical, chemical and electrical characteristics of these sheet samples are examined via X-Ray Diffractogram, NMR, FT-IR, SEM, dielectric property measurement and conductivity measurement.

The performance of these EAPap materials is tested in terms of tip displacement, blocking force, electrical power consumption with frequency, humidity and temperature. The weight percent of MWNT is also important in the electrical and mechanical properties of the material. High concentration ratio will increase the conductivity while low ratio will bring a functionality as sensors and actuators. Thus, an optimal weight ratio of MWNT should be investigated to be smart materials. From the characterization anf performance evaluation results, the actuation mechanism of the new EAPap material will be addressed.

6168-74, Poster Session

Fabrication and characterization of linear motion dielectric elastomer actuators

J. Koo, H. R. Choi, J. Nam, M. Jung, K. Jung, Y. Lee, Sungkyunkwan Univ. (South Korea)

One of the most significant advantages for using EAP actuator is that no complicated mechanical component is needed for generating rectilinear motions. However lack of reliable schemes for assuring controllability of the linear motion produced by the polymeric material actuators hampers application of them to delicate missions. A new design of dielectric polymer actuators that produce linear motions is introduced and fabrication process of the actuators is mentioned in the present paper. A study on the characterization of the fabricated actuators are also elaborated.

6168-75, Poster Session

Effect of reduction temperature on the electrode formation and performance of ionic polymer/metal composites

J. Lee, N. V. Khanh, S. Y. Park, Y. Yoo, Konkuk Univ. (South Korea)

Ionic polymer metal composite (IPMC) was prepared by deposition of platinum (Pt) on NafionTM film via electroless plating consisted of sequential Pt cation reduction steps. In this study, the effect of temperature in each reduction step was investigated. XRD study and SEM of cross-sections of IPMC films showed an increase of Pt density and deposition depth of Pt electrode layer as well as better surface filling at higher reduction temperature, resulting in improved surface and ion conductivity. IPMCs prepared at higher reduction temperatures displayed higher tip displacement, tip force and rate of response. However, some relaxation behavior was observed for IPMC samples prepared at high 1st reduction temperature during bending experiment, partially attributable to the stiffness of thick Pt electrode. IPMC samples were post-treated via additional gold (Au) coating employing ion coater and dc sputtering method. In the case of dc sputtering Au polycrystals with the size of 0.5 - 2.5 μm was formed. On the other hand much smaller Au polycrystals were obtained in the case of ion-coating process effectively filling the gaps between Pt polycrystals. Consequently, the IPMC treated by ion coater demonstrated better performance.

6168-76, Poster Session

Surface electrode for dielectric elastomer actuator using carbon nano tube (CNT)

K. Jung, I. Koo, N. H. Chuc, J. Lee, M. Cho, J. Nam, Y. Lee, J. Koo, H. R. Choi, Sungkyunkwan Univ. (South Korea)

Recently, ElectroActive Polymers(EAPs) are one of the most prospective solutions among the various kinds of smart materials considered as a novel actuator in the near future.1 Also, the electrostatically driven soft actuators based on dielectric elastomer are considered to have high potential to be applicable to practical applications among the EAPs. As reported in the previous researches, the performance of the dielectric elastomer largely depends on the electrical property, especially dielectric constant, breakdown voltage as well as the mechanical property, such as elastic modulus, stress relaxation and viscous damping. Especially, the softness accompanies by the compliant electrode is prerequisite with high conductivity. However, the current technologies for the surface electrode does not satisfy the desired performance due to the degradation of the conductivity on the actuation. In this paper, we propose the carbon nano tube(CNT) as the ideal substitute of the existing technologies. Its superior conductivity over the other materials s.t carbon, graphite is well known, but its application on the dielectric elastomer has not been discussed yet. According to our current investigations, the conductivity of the electrode using CNT is almost 10 times higher than the carbon or graphite. In addition, we has found that charges from the Field Emission Effect of CNT multiplies the conductivity of the electrode, which makes it possible to actuate the elastomer using around several hundred volts of input voltages. Theoretical explanations are given with experimental validations.

6168-77, Poster Session

Viscoelastic studying of conducting polymers using quartz crystal microbalance

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Application of conducting polymers has been growing widely in different fields such as batteries, solar cells, capacitors and actuators. Mechanical properties of conducting polymers like flexibility, high power to mass ratio and high active strain make them potentially applicable to robotic and automation industries.

Obviously, a dynamic model of actuation phenomenon in conducting polymers is needed to study its controllability and also to optimize the mechanical performance. De Rossi and colleagues suggest treating the mechanical behaviour of conducting polymers separately from the viscoelastic structural model and electrochemical actuation. But it has been observed that the effects of electrochemical actuation and diffusion of ions on the viscoelastic coefficients cannot be neglected in some conducting polymer actuators, as shown in [1]. In this paper, we present the effects of cyclic voltametry actuation on viscoelastic properties of polypyrrole in propylene carbonate and TMI.TSFI using an electrochemical Quartz Crystal Microbalance (QCM).

The QCM consists basically of an AT-cut piezoelectric quartz crystal disc with metallic electrode films deposited on its faces. One face is exposed to the active medium. A driver circuit applies an AC signal to the electrodes, causing the crystal to oscillate in a shear mode, at a given resonance frequency. It has been routinely used for the determination of mass changes. Measured resonance frequency shifts are converted into mass changes by the well-known Sauerbrey equation. In this paper, we correlate the admittance output of QCM to the complex shear modulus of polypyrrole. Then the results of the correlation which contains viscoelastic data are presented during actuation using two different types of electrolyte. These results are compared with previous results to show the increased accuracy obtained.

1. Mazzoldi, A., A. Della Santa, and D. De Rossi, Chapter 7: Conducting Polymer Actuators: Properties and Modeling, in Polymer Sensors and Actuators, Y. Osada and D.D. Rossi, Editors. 2000, Springer Verlag. p. 207-244.

6168-78, Poster Session

Mutiple electrode patterning of ionic polymer metal composite actuators

I. Oh, Chonnam National Univ. (South Korea)

The research on the artificial muscle for the implementation of biomimetic actuation becomes a challenging multi-disciplinary topic between science and engineering. The ionic polymer metal composite (IPMC) actuators have been generally manufactured by using electrode plating of Pt on Nafion film with a chemical reduction. Those actuators show a single actuation mode because of the same electrode in top and bottom surfaces. In order to naturally actuate the IPMC actuator, the pattened IPMC with multiple electrodes should be designed by using the etching techique and sputtering methods. The etching techique is a simple way to pattern the pure IPMC manufactured by the chemical reduction. The electrode patterning by using sputtering devices can be made with a precise and repeatable manufacturing process. Present results shows deformation and force characteristics of the patterned IPMC actuators according to the etching and sputtering techiques. For the purpose of the miniaturation of IPMC actuator, the sputtering method is more reasonable regardless of large deformation and actuation forces, while the etching techique is more reliable for the actuation performance.

6168-80, Poster Session

Application of the Monte Carlo method for creation of initial models of models of EAP molecules for molecular dynamics simulation

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The purpose of this work was to create a routine for creating initial models for Molecular Dynamics simulations, capable to arrange at least the followings into simulation cells:

- non-branched polymers,
- branched polymers,
- copolymers,
- nanoparticles,
- solvated salts (ions),
- liquids.

mcgen, a program according to these requirements was written and tested with polymers like Nafion. The optimal values were found for the control parameters the Monte Carlo algorithm depends on, such that the program works steady and fast enough.

Generation features of mcgen allow to:

- generate one or several chains of same or different types;
- add sidechains with fixed or random spacing along the main chain;
- insert atoms and ions into the simulation cell before generating the polymers;
- mark given atoms as “invisible” so that those atoms are not checked against any geometric constraints and will be removed from the simulation cell, if they happen to be on the way of the growing polymer chain;
- establish geometric constraints (sphere, upper and lower limit on one, two or all three axes) and generate polymer chains either inside or outside them.36

When comparing the program with Accelrys Materials Studio, a well-known software package for materials science, it has been found that Materials Studio is easier to use and also produces more relaxed model when the simulation cell is small and sparse. mcgen, the newly created progam however works better under any of the following circumstances:

- more than 524 monomer units in a molecule of poly(ethylene oxide)
- more than 9500 atoms inside a simulation cell
- necessity for more generation steps than Materials Studio can provide
- when on a limited budget
- when one needs to run many generation jobs with some varying parameters

The mcgen program has been attached to the thesis on a Compact Disc. In order to provide te users a possibility to adapt mcgen to their specific needs, the progam has been publicized as open source under the GNU General Public License conditions.

A possible use for the program could be in modelling some fluoro-organic polyelectrolytes and electroactive polymers, incorporating sidechains, e.g. Nafion R for investigation of their properties in Molecular Dynamic simulations. The program might be supplemented to add possibility fo modelling cyclic polymers and polymer with crosslinks.

6168-82, Poster Session

Digital pulse activated cell pump

M. Banister, S. Vohnout, Medipacs LLC

A new array based EAP pump is explored with initial results and design considerations. By developing an array of EAP actuators that are digitally addressable and controlled it is possible to build a pump mechanism with programmable flow rates, psi, flow direction and multiple flows. This provides fluid flow by having a continuous pump chamber consisting of multiple cells that are actuated to an open or

closed position. When closed the fluid in the cell is displaced by the actuator and forced into the next sequential cell that is open. The unique pulse activated cell array format provides the ability to pump in a programmable x & y axis format.

6168-83, Poster Session

Mesoscopic dynamics of piezoelectric copolymer thin films

D. Roy Mahapatra, R. V. Melnik, Wilfrid Laurier Univ. (Canada)

Polymer semiconductors and their composite variants with significant piezoelectric effect are considered as promising candidates to compete with the silicon based technologies, especially for applications in bio-medical industry, micro/nano-scale molecular assembly, and self-sensing-actuating electronic systems. Up to date, several constitutive models have been proposed in literature for polymer chains in solvent as they are solidified. When the dynamics is studied, substantial efforts have been devoted to the analysis of the equilibrium conformations of the polymer chains and their brownian interactions in a non-Newtonian fluid. At the same time, it is known that in the solid state, the dynamics of the resulting active polymer (most often used as thin-film) are governed by the

deformation of the polymer chains that produces electric (or magnetic) polarization and surface charge. Hence, the resulting charge transport coupled with dynamical changes in the conduction band of the polymeric network is of vital importance from the device engineering viewpoint. If the charge transport (generally defined in terms of transport of the positive charges) in a polymer dominates over the molecular polarization such polymers are termed as ionic polymers. Our major focus in this studies is on another category of polymers where the piezoelectricity dominates the dynamics. Electroactive polymeric blends and copolymers based on PVDF provide typical examples of these materials where a large electrostriction (~5%) at ultra high frequencies (~1MHz) may be observed. In this context, a number of applications have already been reported where interaction of laser and UV radiation with piezoelectric polymer thin film is of significant interest. In this contribution, we develop a mesoscopic model of the coupled dynamics involving the time-dependent electromagnetics arising from the interaction of the excitation source term, nonlinear elasticity arising due to deformation of polymer chains, and charge transport. In the numerical studies, we consider electron-irradiated [P(VDF-TrFE)] copolymer, where the Gibbs free energy density is characterized by an ensemble average of conformational energies of the PVDF chains and interaction energies due to random numbers of Tr and FE doping in the blend. Since there exist multiple conformational states, the free energy density is homogenized over a mesoscopic scale. Based on this homogenized free energy density, we derive a new conservation-laws-based model. Numerical simulations aimed at identification of electrostriction patterns under different electric fields are also reported.

6168-84, Poster Session

A solid state actuator based on PEDOT/NBR system: effect of anion size of imidazolium ionic liquid

M. Cho, H. Seo, J. Nam, J. Koo, H. R. Choi, Y. Lee, Sungkyunkwan Univ. (South Korea)

The fabrication of dry type conducting polymer actuator was presented. In the preparation of actuator system, nitrile rubber (NBR) was used as a base material of the solid polymer electrolyte. Thin films of NBR (150 ~ 200 μm) were prepared by compression molding process. The conducting polymer, poly(3,4-ethylenedioxythiophene)(PEDOT) was synthesized on the surface of NBR by chemical oxidation polymerization technique, and the room temperature ionic liquids based on imidazolium salts, 1-butyl-3- methyl imidazolium X [where X= BF4-, PF6-, (CF3SO2)2N-], were introduced into the composite film. The effects of the anion size of ionic liquids on the actuator-displacement were investigated. The displacement increased with increasing anion-size of ionic liquids. The cyclic voltammetric responses and the redox switching dynamics of the actuators in different ionic liquids were studied.

6168-86, Poster Session

Deformation pattern of EAPap bending actuators with frequency and humidity

Y. Kang, W. Jung, Inha Univ. (South Korea); Y. Park, W. J. Craft, North Carolina A&T State Univ.; J. Kim, Inha Univ. (South Korea)

Electro-Active Paper (EAPap) made with cellulose is attractive as smart materials due to its merits in terms of lightweight, dry condition, large displacement output, low actuation voltage, low power consumption and biodegradability. We have observed a large bending deformation from EAPap actuators in controlled environment condition when an electric field was applied on the surface electrodes. So far, based on the cellulose structure and processing of cellulose-based EAPap, the bending deformation of the actuator is caused by the combination of migration and the shear deformation of the EAPap material.

To investigate these actuation mechanisms, the deformation pattern of EAPap is studied under the various parameters. The EAPap material has large portion of region with disordered cellulose chains as well as the ordered crystal region, and water molecules including others can be easily detached to hydroxyl groups of cellulose chains in the disordered regions. When an external electric field is applied, ions and water molecules can be mobile, and migrated to electrode. This results in pure bending deformation of EAPap material due to the expansion of anode or cathode electrode. On the other hand, biopolymers including cellulose exhibit shear piezoelectricity due to the internal rotation of polar atomic groups associated with asymmetric carbon atoms. Interestingly, the shear piezoelectric effect is related with the bending deformation on EAPap actuator. We assume that this bending deformation caused by shear piezoelectricity in monomorph beam of cellulose material may not be pure bending shape. We expect that by investigating the bending deformation pattern, the migration and piezoelectric effects can be determined. Experimental deformation pattern is studied with different humidity and frequency when the alternating current is applied to the EAPap sample, and theoretical calculation will be followed.

6168-87, Poster Session

Effect of bending stiffness of the electroactive polymer element on the performance of a hybrid actuator system (HYBAS)

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An electroactive polymer (EAP)-ceramic hybrid actuation system (HYBAS) was developed recently at NASA Langley Research Center. This paper focuses on the effect of the bending stiffness of the EAP component on the performance of a HYBAS and on theoretical prediction of that performance. For a constant elastic modulus of the EAP component, the effects of length, thickness, and width of the EAP component on the bending stiffness were studied. A theory based on rigid-beam behavior was found to apply above a critical bending stiffness for electron-irradiated P(VDF-TrFE) copolymer. For example, experimental data and theoretical modeling agree for a HYBAS with an EAP length to thickness ratio of 375. However, the beam based theoretical modeling becomes invalid; i.e., the profile of the HYBAS movement does not follow the prediction of theoretical modeling, when the bending stiffness is lower than a critical value. In this case, the EAP element becomes an initially deformed beam. A shell based theoretical model needs to be developed for this situation.

6168-88, Poster Session

Polypyrrole actuators for micropump applications

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Fluid handling devices are commonplace and traditional engineering approaches have enabled pumps to meet many needs. However, nearly all pumps involve ‘moving parts’ that generate wear from frictional losses. The problems associated with pumping small volumes and/or high pressures are also difficult to surmount from traditional engineering approaches. The aim of this programme is to develop a polymer-based pump which can be fabricated to move micro-/nano-liter quantities of fluids with precision. Apart from nanotechnology applications, such as lab-on-chip designs, one possible application of such a pump is within an implantable device which could deliver very small quantities of a highly concentrated drug or hormone at a controlled rate.

Conducting polymer materials are attractive for such applications due to their low voltage operation and the design freedom of the polymeric matrix. Here we will present our initial results on development of both macro- and micro-scale actuating elements based on polypyrrole and substituted polypyrroles, including a spiral polypyrrole single-layer design and out-of-plane micro actuating elements. Standard electrochemical methods, Raman spectroscopy, electron microscopy and mechanical-actuating testing techniques are used to evaluate the actuating elements properties. Preliminary experiments on hybrid conducting polymer/polymer gel actuators will also be presented.

6168-89, Poster Session

New design concept for dielectric elastomer actuators

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A large number of actuator geometries are known for dielectric elastomer actuators. It is known that pre-strain has a beneficial effect on the actuation output properties of dielectric elastomer actuators, though actuators without pre-strain have also been realized and proven to be of value. We would like to present a new concept for design of dielectric elastomer actuators which draws on conclusions from both approaches with, and without a pre-straining frame. With this concept, a large number of new actuator geometries can be visualized, and easily prepared.

6168-90, Poster Session

Electromechanical characterization and modeling protocol for dielectric elastomer actuators

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Dielectric elastomer actuators (DEA) considerably change shape when stimulated electrically and hold promise as artificial muscles. An electromechanical characterization protocol for DEA's is developed and tested with the VHB 4910 acryl elastomer from 3M, where the current - voltage response of the actuator is recorded together with the area expansion from video-extensometry until breakdown occurs. The current is a direct measure of the area expansion of the DEA and can be used to control the actuator. The modeling of the DEA's is based on hyperelasticity models for elastomers. Minimum requirements for the strain energy function of dielectric elastomers are derived in terms of the principal stretching ratios guaranteeing stability against mechanical collapse of the actuator. The electromechanical characterization and modeling protocol developed may provide useful guidelines for the selection and assessment of new dielectric elastomer materials.

6168-26, Session 6

Conducting polymer soft actuators based on polypyrrole films

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Soft Actuators utilizing electrochemomechanical deformation (ECMD) of conducting polymer, polypyrrole films are examined in terms of strain, stress, response time, efficiency and cycle life. The polypyrrole films were prepared in organic electrolyte of methyl benzoate with an ionic solution of tetra-n-butylammonium bis(trifluoromethansulfonyl)imid (TBATFSI) with the condition of 0.2 mA/cm2 for 4 h. The conductivity of the film with thickness of 20 micro m was 80-140 S/cm with spongy morphology. The ECMD strain and stress were more than 26 % and 6 MPa, respectively.

An energy efficiency of ECMD, the ratio of mechanical out put energy to electrical input energy was estimated. The efficiency was found to be less than 0.2% for the polypyrrole films prepared with electrolyte of TBACF3SO3/methyl benzoate. The unexpected small energy efficiency was conjectured to result form the energy consumption to contract the film by itself.

The improvement of response time and cycle life of ECMD as well as current application of the soft actuators are shown. Actuation will be demonstrated by movies.

6168-27, Session 6

Cycling conjugated polymers with different cations

X. Wang, E. Smela, Univ. of Maryland/College Park

The ions present in the electrolyte in which a conjugated polymer actuator is cycled are known to affect performance. Understanding how force, response time, strain, etc. are affected by ion size and other ion characteristics is critical to applications, but is not yet well understood. In this paper, we present the effect of alkali cation mass on transport velocity and volume change in polypyrrole doped with dodecylbenzenesulfonate, PPy(DBS), which is a cation-transporting material. Volume change, measured by mechanical profilometry, was greatest for Li+ and decreased in order of atomic mass: Na+, K+, and Cs+. This was expected because prior studies had shown that the ions are hydrated when they enter the PPy, and Li+ has the largest hydration shell. Ion transport, measured by phase front propagation experiments, was also fastest for Li+, however, contradicting the expectation that larger species would move more slowly.

6168-28, Session 6

Modeling ion transport in conjugated polymers

X. Wang, B. Shapiro, E. Smela, Univ. of Maryland/College Park

Previously, we presented a model for ion transport in conjugated polymers during electrochemical reduction. In this paper, we will present an updated model that includes electron/hole transport, which was neglected in our previous model. This addition allows the model to take into account the interactions between electron and ion transport. The result is that reduced material now propagates with constant velocity, consistent with experimental data from polypyrrole doped with dodecylbenzenesulfonate, PPy(DBS). In addition, the electrolyte has been added to the model, and as a result the ion concentrations behind the phase front are better predicted. This addition also allowed us to test the hypothesis that the experimentally observed saturation of velocity at reduction potentials more negative than -1.6 V was due to diffusion limitations in the electrolyte. However, the model predicted ever increasing velocities at higher potentials, telling us that ion transport in the electrolyte is not the rate-limiting step in that regime. Simply by varying potentials in the model, simulation results match the experimental data from PPy(DBS) upon reduction very well.

This year we also present modeling predictions for the electrochemical oxidation process, running the same model "backwards". The parameters used for oxidation were inherited from those used for reduction. The results were again consistent with experimental observations. Simulated ion concentration profiles show no dependence on applied potential and no phase fronts. The reason for the difference in behavior during reduction and oxidation is that the electric field profiles within the film are quite different. The model shows that during reduction, the electric field changes abruptly across the phase front, whereas during oxidation the electric field varies smoothly across the whole film. The asymmetric initial states, starting with a conductive oxidized state versus an insulating reduced state, create these differences.

6168-29, Session 6

Polypyrrole/gold bilayer microactuators: response time and temperature effects

M. Christophersen, E. Smela, Univ. of Maryland/College Park

Bilayer microactuators of gold and polypyrrole doped with dodecylbenzene sulfonate, PPy(DBS), are being developed in our laboratory for several applications. Last year we presented experimental data and models on the curvature and force of the actuators. In this paper we conclude our characterization with an investigation of the response times and the influence of operation temperature.

The bilayers were subjected to potential steps to switch the PPy between the oxidized and reduced states, and the bending angles were measured with no loads applied. For PPy film thicknesses between 100 and 4,000 nm, the response time, or time it took to reach the final bending angle, was a linear function of PPy thickness (and was independent of Au thickness). Therefore, at these length scales ion transport is not primarily by diffusion. Electrochemical reduction was approximately 1.7 times faster than oxidation. The actuation speed or velocity, defined as the change in angle per unit time, was also examined and found to be different for oxidation and reduction. The speed in the case of oxidation increased rapidly, peaked, and then dropped rapidly until the hinge reached the final curvature values. In comparison, the velocity for reduction increased and then stayed constant. The velocity profiles did not directly follow the current profiles.

The temperature during electrochemical actuation was varied from room temperature to 55 °C. The curvature increased irreversibly by up to 45% at elevated temperatures. The actuators also became 250% faster. However, the force dropped. These temperature effects must be considered when deriving design rules for bilayers used in biomedical applications at body temperatures.

6168-30, Session 6

Fast switching of conjugated polymer films

X. Wang, E. Smela, Univ. of Maryland/College Park

It is important to increase the switching speed of conjugated polymers between oxidized and reduced states for a wide range of devices, including capacitors, electrochromic displays, and actuators. In this paper, we present an engineered conjugated polymer film that responds approximately 100 times faster than a regular conjugated polymer film. A polypyrrole film doped with dodecylbenzenesulfonate, PPy(DBS), was electrochemically deposited onto a gold substrate, and then nano- to micro-scale pores were created in the film. Based on their oxidation/reduction currents and color changes, films with pores responded much faster than films without pores. This is consistent with our previous ion transport studies, which showed that velocities in-plane were much faster than those out-of-plane. Thus, ions are mainly moving in-plane, even though the transport distance out-of-plane is much smaller. Such anisotropy is induced by the DBS anions, which layer the polymer parallel to the electrode surface. Pores allow the cations in the electrolyte (another fast-transport medium) direct access to these layers.

6168-31, Session 6

Soft and flexible actuator based on electromechanical response of polyaniline particles embeded in cross-linked poly (dimethyl siloxane) networks

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Electrorheological characteristics of poly (dimethyl siloxane) (PDMS) networks containing camphorsulfonic acid (CSA) doped-polyaniline (PANI) particles were investigated. Samples were prepared by dispersing fine polyaniline particles into cross-linked PDMS. Rheological properties of the PANI/PDMS blends were studied in the oscillatory shear mode in order to study the effects of electric field strength, crosslink density of the matrix, particle concentration, and operating temperature on their electromechanical responses. The electrostriction of the blends were observed as a result of an attractive force among polarized particles embedded in the network. The sensitivity values of blends are defined as the storage moduli at any applied electric field subtracted by those values at zero electric field, and divided by the moduli at zero field. They were found to increase about 10-50% when electric field strength was increased to 2 kV/mm. These moduli values increased with particle concentration and temperature but they decreased with crosslink density of the matrices.

6168-32, Session 6

Effect of single wall carbon nanotubes (SWNTs) on the electromechanical response of a polyimide nanocomposite

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The mechanical, electrical, and thermal properties exhibited by single wall carbon nanotubes (SWNT) provide strong motivation for their use in composites to develop multifunctionality. SWNTs have been investigated as ionic actuators, but their study as inclusions in the dry state for the purpose of actuation has been limited. The polyimide matrix in this study is non-polar and does not exhibit electromechanical coupling in the pristine condition. Addition of SWNTs as inclusions creates an electromechanical coupling, along with enhanced structural reinforcement and electrical properties, rendering

The SWNT polyimide composite is processed using in-situ polymerization under sonication, to obtain a composite with uniform dispersion. Electrical conductivity and dielectric constant values are calculated at different SWNT concentrations and at different frequencies (20 Hz - 1 MHz). A percolation transition is observed at 0.05 vol% SWNT loading. Figure 1 shows the conductivity of the composite at different SWNT loading. There is a sharp increase in the conductivity at 0.05 vol%;this is indicative of a percolation transition. Also, the conductivity increases with frequency up to 0.05 vol% SWNT concentration. Above it, conductivity remains constant with frequency thus indicating a change in the nature of the composite from an insulator to that of a conductor.

Thin strips of the sample of thickness around 50 microns are tested using DC and AC electric fields as stimuli. The sample strip is suspended vertically as a cantilever and a voltage is then applied through the thickness. The strip bends and its bend increases with an increase in the applied voltage. For DC voltage, bending is observed in the same direction, regardless of the polarity of the voltage. The extensional strain is calculated from the tip displacement, modeling the bent strip as a cantilever beam under a uniformly distributed load. In this case, the length extensional strain (S) is given in terms of the tip displacement (w), the thickness of the strip (t) and the length of the strip (l) by -

$S = 2*w*t / l^2$ (1)

Figure 2 shows the dependence of the strain on the electric field and SWNT loading.

The strain increases with the electric field and with SWNT loading until 1vol%.Above 1vol%, a slight decrease in the strain is seen. When plotted against the square of the electric field, the strain data shows a linear trend. These quadratic fits are also shown in Figure 2. Based on the experimental data, the actuation mechanism proposed is bending electrostriction, which is due to quadratic non-linear electromechanical coupling in the material. The electrostrictive strain is given by:

$S13=(M1333)E3^2$

$=(Q1333)P3^2$

$=\varepsilon 0^2(\varepsilon 33-1)^2(Q1333)E3^2$ (2)

Where,

S13 = length extensional strain

M1333= coefficient of electrostriction related to the electric field

E3= electric field applied across the thickness of the strip

Q1333= coefficient of electrostriction related to the polarization

P3= polarization vector

$\varepsilon 33$= dielectric constant

$\varepsilon 0$= permittivity of vacuum

The electrostriction coefficient related to electric field, M1333 is thus calculated and the effect of SWNT loading on the coefficient is studied. The strain rate as a function of time is calculated and compared at different SWNT loading.

The three main observations with the DC test are; 1) The strain is proportional to the square of the electric field. 2) Strain increases with the increase in the SWNT concentration until 1 vol%. 3) It shows a slight decrease above 1 vol%, indicating a plateau in the strain as a function of SWNT content. Similar observations are made by carrying out experiments using AC field. Calculations for electric field in this case are carried out using the peak-to-peak voltage.

The increase in the dielectric constant with SWNT concentration can account for the reason why the electrostrictive strain increases with increase in concentration. The electrostriction coefficient related to electric field depends on the dielectric susceptibility of the dielectric material and hence the dielectric constant, which in turn increases with an increase in SWNT concentration. This relationship can be inferred from Figure 1 and Equation (2). This also accounts for why the strain plateaus after reaching a certain concentration, as similar behavior is also observed for dielectric constant (Figure 1).

In summary, actuation is observed and measured above the percolation threshold where the composite behaves as a conductor. Also, based on the actuation measurements under DC and AC field , it can be concluded that the addition of SWNTs in the polyimide gives rise to an electromechanical coupling in the nanocomposite. The actuation mechanism observed is electrostriction, which increases with the increase in the SWNT concentration up to a certain concentration. Above this value a slight decrease is observed in the strain indicating a plateau in the behavior.

6168-33, Session 7

Modeling of charge transport and electromechanical coupling in ionomeric polymer transducers

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Recent work by our group has demonstrated that a one-dimensional transport model combined with an electromechanical coupling model can predict the step response and harmonic response of ionomeric polymer transducers. The transport model is solved using a discrete approximation to the nonlinear transport equations. The result is a computation of the volumetric charge density as a function of space and time. The localized stress is assumed to be a summation of a linear function of volumetric charge density and a quadratic function of volumetric charge density. Measured step response date illustrates that the current discharge of the polymer can be accurately modeled by determining the diffusion coefficient and permittivity of the ionomer substrate. Accurate simulation of the current discharge allows computation of the harmonic electrical impedance of the transducer subjected to sinusoidal voltage excitation. Correlation of measured impedance response with simulation demonstrates that the model is able to adequately predict the trends in the peak-to-peak current amplitude as well as the phase between the applied voltage and induced current. The model of localized stress is incorporated into a beam mechanics model and measured data is compared with predictions of the bending strain for a step change in voltage and a harmonic voltage excitation. Comparisons of predictions with measurements demonstrate that the model accurately predicts the trends associated with the peak-to-peak strain over two decades of frequency response (0.1 Hz to 10 Hz) and the amplitude of the strain output to a step change in voltage. Most importantly, the step response data clearly illustrates the need for a linear and quadratic relationship between volumetric charge density and induced stress. A linear relationship between these two parameters would not be able to capture the nonlinearity in the strain output as a function of step voltage potential. These results demonstrate that a one-dimensional transport model coupled to an electromechanical model of localized stress generation can produce an accurate static, quasi-static, and harmonic response model for ionomeric polymer transducers.

6168-34, Session 7

Fluid interaction of segmented ionic polymer-metal composites under water

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The numerous potential applications of Ionic Polymer-Metal Composite (IPMC) as an underwater propulsor have lead to the investigation of the IPMC behavior in an aqueous environment. This study compares the performance of the IPMC when

subjected to fluid drag forces to its performance without such forces. Both the form (i.e. pressure) drag and the viscous (i.e. skin friction) drag forces experienced by the IPMC due to the surrounding liquid are modeled. These forces are incorporated into an existing analytical model of a segmented IPMC which adequately models the relaxation behavior of the IPMC. The hydrodynamic model developed is 2-dimensional. The maximum IPMC deflection and amount of relaxation predicted for aqueous and non-aqueous environments are compared. IPMC material properties are also varied to determine the effect on the IPMC performance. Results from this model are used to assess the suitability of the IPMC for underwater use.

6168-35, Session 7

Electro-chemo-mechanical interpretation of ionic polymer-metal composites electroded with Pt, Au, and conducting polymers

D. Kim, K. Kim, Univ. of Nevada/Reno

The necessity of selecting a reliable electrode-material for Ionic Polymer-Metal Composites (IPMCs) is well recognized. Known electrode-materials of current interest include platinum, gold, and conducting polymers. Until now there has been few studies on electrochemical behaviors of the electrode-surface of IPMC. In general, the electrochemical reactions under imposed electric fields cause the variation of resistance and capacitance of IPMC and, thus, lead to the changes in the bending profile of IPMC. This paper describes the electro-chemo-mechanical interpretation of the electrode made with Pt, Au, conducting polymer, and hybrid systems of interest—Pt/Au, Pt/conducting polymer, etc. The conventional electrochemical analyses including voltammetry, electrochemical impedance spectroscopy, and capacitance measurements on the electrode surface were carried out in aqueous and non-aqueous solutions, respectively. The redox behaviors over a wide potential range were measured by the cyclic voltammetry method. The experimental results recommend the selection of appropriate electrode materials, solvents, and operation conditions.

6168-36, Session 7

Multifields responsive ionic polymer-metal composite

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We first report the successful development of an Ionic Polymer-Metal Composite (IPMC) which exhibits both magnetic and electrical responses. Such IPMCs were fabricated with precipitated iron oxide particles within the ionomer matrix using an appropriate iron salt reduction technique. We found that the precipitation of iron oxide within a Nafion membrane induces a good magnetically responsive behavior of IPMC. The SEM cross sectional view of particle precipitated (ppted) layer was measured along with EDS. Also, the vibrating sample magnetometry of ppted iron oxide/Nation was performed to verify the paramagnetic characteristics of the fabricated IPMC. The ppted layer was approximately 2.5 μm. We observed that the iron oxide was well formed at the outer layer of IPMC. It should be noted that the ppted iron oxide/Nafion IPMC inherently shows fast oxidation that often causes high electric resistance.

6168-37, Session 8

Effect of nanoparticulate fillers on the deformation behavior of nafion-based IPMC

N. V. Khanh, J. Lee, H. T. Lim, Y. Yoo, Konkuk Univ. (South Korea)

Incorporation of small amounts (3-7 wt%) of nano-particles such as layered silicate, silica, and CNT may greatly alter some important mechanical and electrical properties of Nafion matrix. These fillers can be easily modified and functionalized to implement unique properties for the performance of IPMCs. Our recent study indicates that Nafion/MMT, Nafion/silicates composites can be prepared with nanoscale dispersion. Most of IPMCs based on Nafion nanocomposite exhibit improved displacements and blocking forces compared to pure Nafion based IPMC. Due to the barrier property and hygroscopic nature of silicates, water loss of IPMC under dc voltage is greatly reduced, which is significant in term of IPMC performance durability. In the case of Nafion / layered silicate nanocomposite, however, response is slow due to the barrier effect of the clay platelet; while in Nafion / silica and Nafion / CNT systems, response rate is comparable with that of conventional IPMC. Improvement in mechanical properties and relaxation was achieved without any significant loss of other important properties.

6168-38, Session 8

An analysis of increase of bending response in IPMC dynamics given uniform input

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Ionic Polymer-Metal Composite (IPMC) can operate in water by specifying low voltage, therefore it is a hopeful actuator for underwater robots. Many underwater swimming robots are controlled to mimic fin motion of living creatures because it gives a high propulsive efficiency. Living creatures such as snakes, rays, or squids can swim by generating progressive waves on their bodies or fins.

When such living creatures swim in water, amplitude of oscillatory motion increases from forward to backward along their swimming direction. It is also found from the locomotion of swimming robots using IPMC as their actuators that, although we specify the same amplitude of driven voltages to each unified IPMC unit, the resultant bending amplitudes along the fin's progressive wave change from small to large along the robot's moving direction. In contrast to the conventional underwater robots using geared motors, the robots using IPMC have soft bodies and their control variables are moment instead of deflection. In other words, the swimming robots using IPMC are usually controlled by voltage which is related to the moment. The phenomenon of increasing amplitude of bending response naturally appears in spite of uniform moment input. This may also imply that the living creatures control only their bending moment instead of their shape of motion.

In order to analyze the phenomenon, it is necessary to model the dynamics of the robot. Furthermore, modeling of the dynamics will be essential in order to design the optimal control input or/and the optimal shape of the fin for a control objective. Modeling is also important to understand the swimming form of living creatures.

In this paper, we first propose a deflection model of IPMC using Euler-Bernoulli beam theory. The model described by a linear partial differential equation can represent the dynamics of the deflection which is perpendicular to the direction of the propulsion. Equivalent inertial and viscous forces are considered although fluid mechanics is not used. The solution of the model can be obtained by eigenfunction expansion technique. The envelope curve can also be drawn by the obtained solution. Secondly, we measure the dynamic shape of snake like robot using IPMC in the experiment. A laser device and a video camera are used to capture the motion. The captured image is processed and is fitted by a series of the eigenfunctions. Simulation is also performed to compare with the experiment. Its result reappear the same phenomenon. Finally, we conclude with a summary and some notes on the relevance of the model.

6168-39, Session 8

Characterization and dynamic modeling of IPMC 'artificial muscles'

A. Mudigonda, J. Zhu, Ohio Univ.

This paper deals with the characterization and dynamic modeling of the Ionic Polymer Metal Composite (IPMC) 'artificial muscle' materials. Using indigenously constructed data acquisition system made for measuring small forces, displacements and currents, experiments were performed to characterize the behavior of two types of IPMCs. Environmental Robots, Inc. (ERI) was the initial vendor and its IPMC products required hydration for optimal performance. Virginia Polytechnic Institute and State University (Virginia Tech, VT) subsequently developed their innovative ionic solvent filled IPMCs that obviated hydration. Static tests were conducted to characterize force, displacement and current as a function of applied voltage. Dynamic tests were conducted to observe the frequency response of the material. Fatigue tests were performed on the ERI IPMCs to observe the change in behavior over time. It was found that the VT IPMCs had a bandwidth that was almost half that of the ERI product. However, the obviation of hydration of the VT's IPMC ensured the repeatability of performance and generated increased force densities.

6168-40, Session 8

Degradation mechanism of ionic polymer actuators containing ionic liquids as a solvent

S. D. Pandita, H. T. Lim, Y. T. Yoo, H. C. Park, Konkuk Univ. (South Korea)

Ionic polymer metal composites (IPMCs) have been widely studied because they exhibit an actuation phenomenon at relatively low applied voltage. Currently, water is used as solvent for the actuation process. However, water has some limitations. Water easily evaporates at the ambient temperature and is hydrolyzed at 1.22 volt. As a result, IPMCs with water have poor performance in dry environment. Ionic liquids are organic compounds which exhibit extremely low volatility, large electrochemical window, good conductivity, and excellent thermal stability. Ionic liquids have been recently introduced to replace water for IPMCs. The im-

pregnation process was carried out by immersing ionic polymers in the mixture of ionic liquids and alcohols. Alcohols were required as a carrier since ionic liquids are hydrophobic whereas ionic polymers are hydrophilic. It is shown that the durability of IPMC with ionic liquid as solvent increased significantly. However, during the impregnation process, ionic polymers demonstrated a large swelling resulting in lower surface conductivity and hence give lower actuation performance. In this research, the surface conductivity of IPMC with ionic liquid as solvent is implemented by employing a gold coating after the impregnation process. Nafion (r)117 with platinum electrodes and 1-Ethyl-3-methylimidazolium trifluromethanesulfonate (ionic liquid) were used in this study. During the actuation process, some ionic liquids was squeezed out and accumulated on the surface particularly at relatively high voltage (3 V) and high frequency (more than 1 Hz). Consequently, ionic liquids inside the ionic polymer depleted. Polyurethane coating was employed in order to minimize the solvent loss. In this paper, the actuation response, durability and the degradation behavior of the ionic polymers with ionic liquids will be reported.

6168-41, Session 8

Fabrication and characterization of linear-moving in-air ionic polymers actuators with design and motion simulation tools

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Among electroactive actuators, ionic actuators (such as conductive polymers and IPMC) have several advantages (softness, low actuation voltages, high deformations) but also drawbacks (they need a solvent, and their classical beam-shape exhibits bending movements only).

In this paper, we will evaluate the performances of a fabrication method which was conceived to devise EAP actuators working in air and producing a linear motion rather than a bending one. The reference materials with which we worked are the interpenetrated polymer networks with conductive polymers (IPN-CP) which are made following Vidal's procedure. Nevertheless, several elements of this study can be extended and adapted for IPMC-based EAP, which can be fabricated following a similar technique to the hereafter presented one.

In Vidal's procedure, an elastic polymer film which is made from several interpenetrated polymers is prepared in a first step. Then, a liquid monomer is introduced and will be polymerized in a second step, to form a conductive polymer which is interpenetrated in the film. This polymer forms at the surfaces of the film, which then become electroactive electrodes. This polymerization, which creates the electroactive parts, can be controlled independently.

The use of this property enabled us to make inhomogeneous polymerizations at the surface of IPN-CP, to obtain a material with both polymerized and not-polymerized areas in the same material. Thus, there will be both electroactive zones, which are deformed under a voltage, and not-electroactive zones, which are elastic. Subsequently, obtained actuators can have various shapes that engender several appropriate motions (which are very different from classical bending ones).

We conceived 3D computer simulation software of the movement and the mechanical behavior of the actuators, which is based on finite-element simulation methods. It allowed us to predict the movements of the actuators as a function of their shape and of the layout of polymerized areas. Thanks to the simulation, we show that the polymerization of clearly defined areas enables us to obtain linear movement actuators, with, moreover, a possible integration of the power supply wiring. However, inhomogeneous polymerization leads to high mechanical stresses during the fabrication, between polymerized rigid areas, which inflate during the process, and not polymerized soft areas, which inflate at first and then go down, during the process. Consequently, masks techniques cannot be used to control the polymerization layout.

We show how it was possible to solve this problem thanks to well-controlled contactless injections of polymerizing agents. We designed a dedicated "robot" that we will present, to perform accurately this tricky step, with a precise control of the polymerization locations and time.

We present several linear and air moving actuators that were obtained this way. Their performances (force, displacement, speed) as a function of the voltage will be presented and compared to simulation results for each of these non-homogeneously polymerized actuators.

6168-42, Session 8

Characterization of IPMC actuators using standard testing methods

D. Fernandez, R. Espinosa de los Monteros, L. Moreno, J. Baselga, Univ. Carlos III de Madrid (Spain)

In response to a clear need, the EAP (Electroactive Polymer) research community has just started to work on a standard test methodology to characterize EAP actuators. A very general test methodology for EAPs, covering the characterization procedures for extensional and bending actuators was recently presented by an international working group.

In the present work, well known IPMC samples are charecterized following the proposed standard test methodology. Aldo, additional tests, not covered by the preliminary standard are included. These tests are conducted using the EAP Unit Tester, a test bench specifically designed for the characterization of EAP actuators. Rather than presenting new material's results, the paper focuses on the instrumentation, procedures and form of presenting results.

Although the paper is focused on IPMC the method can be extrapolated to other bending actuators such as those based on conducting polymers or carbon nanotubes.

6168-43, Session 9

From smart implants to soft robots: the hope and hype of artificial muscles

S. Rajagopalan, École Polytechnique de Montréal (Canada) and McGill Univ. (Canada)

Artificial muscles were supposed to bring about a revolution in robotics and prosthetics, yet more than a decade later, the science continues to lag behind the hype. With the research community still grappling with fundamental issues, notions like brain-controlled artificial muscles, snake-like robots or actively-controlled flexible structures will remain confined to laboratories for a long time to come. Clearly a paradigm shift is needed to break this scientific stalemate.

Part of the solution would be to adopt a holistic, systems approach to designing artificial muscles. Design of artificial muscles ought to go hand-in-hand with the design of an appropriate control and feedback system, much like the nerve fibers that control muscle contraction. Secondly, we would need to move away from monolithic structures to design modular, hierarchical structures, akin to biological muscles - while allowing for discrete control of individual actuating units. The ultimate objective would be to mimic "turn-over" or the renewal and repair of biological materials.

This paper addresses some of these pressing challenges with work carried out by the author toward an integrated neuromuscular implant. Here, through electrochemical synthesis, the electron-conducting properties of polypyrrole are combined with the ion-mediated actuation of sodium polyacrylate to create a controllable actuator. Biomechanical measurements in simulated physiological fluids bear striking resemblance to biological muscles. The polypyrrole interface has been shown to capture electric signals from nerve fibers and can potentially be part of a nerve-responsive artificial muscle. Feedback is provided by the ion outflow from the polyacrylate gels during stretching and contraction. The integrated implant displays muscle-mimetic properties in-vivo.

Also, as part of the new biological motors program sponsored by DARPA, an eel-like robot is under development. Here ion exchange membranes are combined with charged hydrogels to create undulating motion through charge migration across the material. Polypyrrole is added both to improve ionic conductivity and for use as flexible electrodes. Many of the same issues affecting the neuromuscular implant come into play when designing soft robots - including distributed, adaptive control systems and modular vs. monolithic designs.

6168-44, Session 9

Buckling dielectric elastomer actuators and their use as motors for the eyeballs of an android face

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The FACE (Facial Automaton for Conveying Emotions) project in course at the Interdepartmental Research Centre 'E. Piaggio' of University of Pisa is aimed at developing an android face endowed with dynamic expressiveness and artificial vision. The bionspired approach behind the development of this system foresees the adoption of electroactive polymers as pseudo-muscular actuators to provide motion to the skin of FACE, as well as to its eyeballs. The eyes of such a human-like automaton, and in particular the achievable movements of them, play a relevant role for the 'believability' of the overall system, and thus of its effectiveness, as well as for the performance of the embedded artificial vision. This work presents preliminary results related the actuation of the FACE eyeballs by means of a new type (buckling) of dielectric elastomer actuator. This kind of actuator operates with out-of-plane unidirectional displacements. It is similar to the diaphragm-type one, with the difference that the necessary pre-deformation is enabled by an underlying hemispheric support, instead of pressurised air. One silicone-based buckling actuator was connected to a plastic eyeball of FACE via a tendon-like

wire, in order to enable unidirectional rotations. Relative out-of-plane displacements of the actuator larger than 50% were achieved and used to provide rotations up to 13 degrees.

6168-45, Session 9

Activation of dielectric elastomer actuators by means of human electrophysiological signals

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The assessed high electromechanical performances of dielectric elastomer actuators are encouraging the study of possible future applications of such devices for active prosthetic systems for humans. Although the high electric fields currently needed for their driving prevent today a short-term use in endo-prostheses, their adoption for eso-prostheses can be considered more realistic. Exoskeletons for improving muscular performance in specific tasks or for rehabilitation are examples of possible fields of investigation. In parallel to a necessary technological development towards materials and devices capable of improved performances at reduced fields, the study of such applications requires even the identification of suitable strategies of activation and control. In particular, actuators for prostheses or exoskeletons may take advantage from the possibility of being activated by electrophysiological signals. This would consent advantageous body's controls of the artificial system. In this context, this work presents activities carried on to achieve such a goal. Activations of silicone-made dielectric elastomer actuators by means of different types of electrophysiological signals opportunely elaborated are presented and discussed.

6168-46, Session 9

An MRI-compatible tactile display device based on IPN-CP pastille-shaped actuators

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Nowadays, thorough psychophysical and neuroscience studies to better understand the human haptic modalities require functional MRI (fMRI) investigations. Subsequently, MRI-compatible haptic display technology is necessary to stimulate human skin parts in a controllable manner and at different locations. Haptic devices used to display kinesthetic or tactile stimuli, require actuators. Stimulation of human tactile mechanoreceptors is made classically through matrix arranged actuated pins. Existing efficient actuators technology for tactile displays is based on electromagnetic technologies, like electrical motors. But, IRM techniques require very high magnetic fields making classical actuation technologies useless for those studies.

The use of artificial muscles based on electro-active polymers is proposed as an alternative to conceive a tactile display. Therefore, this paper presents an MRI-compatible tactile display prototype that has been conceived based on our past experience in haptics and EAP. The tactile display is also designed as 3Å~3 matrix-arranged pins. Each pin is actuated independently and in a direct way (i.e. no intermediary motion or force amplification mechanism is used).

Each actuator is based on the IPN-CP actuation technology, i.e. it is made of an Interpenetrated Polymer Network as solid polymer electrolyte, and conducting polymer, interpenetrated with the electrolyte, as electrodes and electro-active parts. In previous papers, we have achieved a complete characterization of such actuators. Actuators have a pastille shape with an additional integrated power supply canal, which is also made of IPN-CP. This shape has been chosen to enable a linear actuation instead of a bending one, and to permit to place the external electrodes far from the actuation center, to prevent them from reducing the actuation strength. The pin is placed at the center of the pastilles (of circular form) which transform into semi-spherical forms after actuation. In this way the forces are concentrated on the highest point of the semi-spherical pastille (positive voltage). The total achieved length is nearly the diameter of the pastille if negative to positive voltage are applied.

Actuators dimensions were chosen so that the force is sufficient to be well perceived by the human haptic modality. In this first prototype, each actuator has a 10mm diameter. The current supply canal dimensions were chosen so that the mechanical resistance of the canal is the best possible, without being too large, to prevent bad actuation performances. Additional studies concerning the response of the actuator element, as a function of various relevant parameters (voltage, control signal shape, actuation time, external stresses, etc.), have been performed to evaluate their performances (force, displacement, speed). We studied also the open-loop and closed-loop control of the actuator. We investigate which control laws are the most efficient to increase the performances of the actuators, which have a response that is strongly non-linear with the voltage.

This paper discusses also other parts of the haptic display, namely: its mechanical design (contacts, wiring, external electrodes, force conveying pins, mechanical guides, etc.) and its driven electronics design as well (control, amplification and addressing circuits). We present its working principle and its global performances during preliminary actual use.

6168-47, Session 9

Modeling of ionic polymer-metal composite (IPMC) beam on human tissues

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Ionic polymer-metal composite (IPMC) is a type of wet electro-active polymers (EAP). It consists of a thin polyelectrolyte membrane and a type of noble metal, such as gold and platinum, chemically plating on both sides of the membrane. IPMC can undergo a fast and large bending motion when a low electric potential is applied to its electrodes. Conversely, IPMC will generate a measurable electric potential when it is subjected to a sudden bending. Thus, the IPMC can sever as both actuators and sensors. Although some theoretical and empirical models have been developed to account for the electromechanical behavior of IPMC, the actuation mechanism of IPMC has yet been fully understood. Nevertheless, research on applications of IPMC has attracted considerable attention from various disciplinaries. IPMC offers many advantages over the conventional EAP materials, such as compliance, light weight, low operation voltage and capability of working in aqueous environments. These properties make it promising for numerous applications in biomedical, naval, robotic and microelectromechanical system (MEMS) engineering. One of the important applications of IPMC is biomedical related instruments which contact with human organs or tissues such as artificial ventricular muscles, surgical tools and active scleral bands. The configuration of IPMC materials could be in various forms including bands, rings and beams.

Since IPMC materials are generally expected to work in a vibration state, it is necessary and meaningful to investigate their dynamic behaviors. However, in the literature, little research has been reported to investigate the dynamic behaviors of IPMC materials. In this paper, an analytical model is developed to depict the vibrational response of a simply-supported IPMC beam resting on an elastic foundation under alternative electric fields. The elastic foundation is employed to simulate the effect of human tissues. Nemat-Nasser's hybrid actuation model is incorporated in the motion equation with modifications to account for the applied alternative electric field. A closed-form solution is obtained to describe the transverse vibration of the IPMC beam to the command of an applied electric field. Based on this solution, the pressure generated on human tissues is calculated by numerical integration. Preliminary experimental test is conducted to verify the displacement solution. A light-weight accelerometer is used in the experiment to obtain the displacement of certain point on the beam. Comparison shows that the theoretical model is in good accord with the experimental data. The developed model is useful not only for the biomedical devices that employ IPMC materials but also for any other applications that utilize the vibration of IPMC materials.

6168-48, Session 9

Packaged Au-PPy valves for drug delivery systems

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The most common methods for the drug delivery are swallowing pills or receiving injections. However, formulations that control the rate and period of medicine (i.e., time-release medications) are still problematic. The proposed implantable devices which include batteries, sensors, telemetry, valves, and drug storage reservoirs provide an alternative method for the responsive drug delivery system. Using this device, drug concentration can be precisely controlled which enhances drug efficiency and decreases the side effects. In order to achieve responsive drug delivery, a reliable release device (e.g., a valve) has to be developed. Biocompatibility, low energy consumption, and minimized leakage are the main requirements for such release method.

In our previous work , the valves feature a bi-layer structure where one layer is a thin metal film, functioning as a structural layer and a working electrode, and the other layer is a polypyrrole (PPy) film electrochemically deposited on the working electrode. The actuation mechanism of the valve is based on ion flux in and out of the polypyrrole film upon oxidization and reduction. The volume change of the polypyrrole film forces the bi-layer to bend resulting in the opening and closing of the valve. The voltage applied for actuation is less than 1 V and the current is lower than 1 mA for an actuator with a flap area of 0.04 mm2. Although we have demonstrated that the valve can be opened and closed repeatedly by cycling the voltage between negative and positive values, there is a need to prevent valve blockage by muscle or tissue. Therefore, a protective device packaging is required.

In this work, we propose a novel idea to simultaneously fabricate the device reservoirs as well as protective packaging. A piece of poly dimethyl siloxane (PDMS) with an array of reservoirs has been molded and sealed on the substrate to cover

the flap valves. The PDMS chip can serve as the package to shield the valve from outside environment and it can also function as the reservoirs to store the therapeutic agents. The liquid medicine provides an aqueous environment suitable for the PPy actuation. An electrochemical detection method is used to test the drug release function. A testing platform with a channel and two reservoirs is fabricated on an acrylic chip. Then the channel is filled with D.I. water and two electrodes are inserted into the reservoirs. The salt solution (3M NaCl) that mimics the aqueous therapeutic agent is stored in the PDMS reservoirs. Under a constant voltage (1V), the current increases tenfold within 2.5 min after the release of NaCl solution from the valve. Then current tends to plateau. It is believed that this novel fabrication approach can be profitably extended to the new generation of the drug delivery devices.

6168-49, Session 9

Developing multilayer dielectric elastomer actuators for augmenting human movement

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Developments in smart materials based on electro-active polymers (EAP) are expected to provide a basis for the development of new artificial devices that supplement natural muscle, such as wearable exoskeletons. However, many challenges still remain on the road to practical applications.

The goal of this research is to develop low-profile, flexible, body-shape conforming actuator designs suitable for integration into a glove-like exoskeletal device. Its purpose is to provide some gripping assistance to people with disabilities rather than augmenting normal human strength. This work is part of a larger program on assistive devices for the disabled, which for this application is those with certain cervical spinal cord and brain injuries as well as degenerative muscular/neurological conditions such as multiple sclerosis. A power-assisted glove or Smart Grip that enables certain types of lightweight manipulation requires relatively small actuation forces yet can have a large impact on the quality of life and care requirements for these patients. Although a number of pneumatic or mechanically actuated hand orthoses have been developed, they are generally quite obtrusive and have low rates of user adoption.

Because of their solid-state nature, large strain and energy density capabilities, dielectric elastomers (DE) are among the most promising of EAP materials. The successful implementation of DE-based devices depends in part on the development of actuation arrangements that convert Maxwell pressure and dielectric deformation into the desired motions and forces. Strain levels compatible with artificial muscle function are well within the capabilities of acrylic and silicone dielectric elastomers, but the low elastic modulus of these materials means that a multilayer assembly is needed in order to achieve significant forces. A laminated construction also allows the required driving voltages to be reduced, which is an important consideration for wearable applications.

This paper presents results for experiments in active and passive characterization of single and bilayer dielectric elastomer actuator specimens with different electrode films. These results are compared with the predictions generated by both conventional and meshless finite element dynamic models that include the hyperelastic and stress relaxation behavior of the material, and also investigate their performance under the large strains implicit in this application. The scale effect of multiplying the number of layers while varying their thickness is examined through analysis. These modeling methods are then used to study the design of small-diameter anisotropic cylindrical DE actuator configurations that could be incorporated easily and unobtrusively in a glove. This cylindrical configuration is believed to be novel for EAP actuators, and preliminary design results and risk reduction tests are presented.

6168-59, Session 10

Modeling of EAPs as multiple energy domain systems: a bond graph approach

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Electro-Active Polymer (EAP) actuators inherently involve energy flow in multiple energy domains: mechanical, electrical, and at times, chemical and thermal. However, a complete predictive model explaining the behavior of EAPs has not yet been reported because of their complexity, particularly regarding the coupling phenomena between several energy domains. In this paper, we develop a model of EAPs suitable for dynamic simulations. The model uses bond graph methods as bond graphs are particularly appropriate for systems with multiple energy domains. Specifically, we develop a bond graph model for a conjugated polymer that behaves as an extensional electrolyte storage actuator using one cation- and one anion-exchanging polymer as proposed by Lewis, et al.

There are four aims in developing bond graph models of conjugated polymers. First, we seek to permit identification of known and as yet, unknown material properties of the elements in the system as a guide for future research by chemists and material scientists. Second, the model should allow analytical evaluation of important questions such as what behavior determines the time constants and efficiency of the system. Third, the model will enable design simulations which can provide guidance for best parameter choices for new devices. This is an important step in the maturing of our knowledge of conjugated polymer actuators - the design to optimize particular aspects of the behavior and to downplay or minimize other characteristics in order to achieve desired performance. Fourth, the model should serve as a template for models for other sorts of EAP actuators such as IPMCs and gel-type electroactive polymers. By developing bond graph models of these additional EAP actuators one could consistently compare the advantages and disadvantages of each EAP actuator type.

For system under study, the diffusion process of those ionic species resulting from the applied electric potential, the chemical reactions in the reduction and oxidation processes, and the resulting volume change of the three layers are represented using separate bond graph models which are then connected appropriately to form a single bond graph model of the entire system. The coupling phenomenon of the three energy domains (mechanical, chemical, and electrical) is explained by using a three-port capacitance element derived from the Gibb's free energy. The resulting bond graph model includes many phenomena which have been neglected in previous models of EAPs. In particular, our model includes significant resistance elements representing the resistance inherent in the diffusion process and the chemical reaction, the frictional coupling between the ionic solutes and solvent, and the frictional coupling between the ionic solutes.

The organization of this paper is as follows. Section II briefly introduces concepts of the bond graph modeling approach. Section III presents bond graph models for the diffusion process of a binary flow going through a membrane, a chemical reaction, and a combined diffusion-reaction process. These basic models are then applied to modeling of forced diffusion and an extension-type conjugated polymer in section IV and V, respectively. Finally, we draw conclusions.

6168-60, Session 10

Multiscale modeling of polyelectrolyte gels

T. Wallmersperger, F. K. Wittel, B. H. Kröplin, Univ. Stuttgart (Germany)

Electrolyte polymer gels are a very attractive class of actuation materials with remarkable electronic and mechanical properties having a great similarity to biological contractile tissues. They consist of a polymer network with ionizable groups and a liquid phase with mobile ions. Absorption and delivery of solvent lead to a considerably large change of volume. Due to this capability, they can be used as actuators for technical applications, where large swelling and shrinkage is desired.

In the present work chemically and electrically stimulated polymer gels in a solution bath are investigated. To describe the different complicated phenomena - occurring in these gels - adequately, the modeling can be conducted on different scales. Therefore, models based on the statistical theory and porous media theory, as well as a multi-field model and a discrete element formulation are derived.

A refinement of the different theories from global macroscopic to microscopic are presented in this paper:

The statistical theory is a macroscopic theory capable to describe the global swelling or bending e.g. of a gel film, while the general theory of porous media (TPM) is a macroscopic continuum theory which is based on the theory of mixtures extended by the concept of volume fractions. The TPM is a homogenized model, i.e. all geometrical and physical quantities can be seen as statistical averages of the real quantities. The presented chemo-electro-mechanical multi-field formulation is a mesoscopic theory. It is capable of giving the concentrations and the electric potential in the whole domain. Finally the (micromechnical) discrete element theory is employed. In this case, the continuum is represented by distributed particles with interaction relations combined with balance equations for the chemical field. This method is predestined for problems envolving large displacements and strains.

The presented formulations are compared and conclusions on their applicability in engineering practice are finally drawn.

6168-61, Session 10

Theoretical and experimental investigations of fundamental effects in carbon nanotube sheet actuators

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In this paper we present experimental measurements as well as a theoretical model for the chemo-electrical and mechanical behavior of Carbon Nanotube (CNT) ac-

tuators.

Carbon nanotube actuators are chemo-electro-mechanical converters and exhibit very promising material parameters (i.e. extremely high elastic modulus, higher stresses than natural muscles and higher strains than many other electroactive materials).

To describe the electrical conductivity and the charge transfer process occurring in the CNT sheets, the chemo-electrical behavior is described by a coupled micro-mesoscopical model. By applying an electrical field to the CNT material within a chemical environment, this model is capable to show the double layer process leading to an asymmetric charge distribution in an actuator consisting of Carbon Nanotube films laminated together with an insulated film material in between.

In the experimental part, fundamental tests have been realized to demonstrate the basic actuation behavior of these materials. We have investigated some fundamental test configurations where the geometry and surface conductivity of the bucky paper probes and the electrical contact to the probes have been varied.

Based on these fundamental effects we are able to confirm the theoretical model and to develop more sophisticated actuators.

6168-62, Session 11

Fuel powered artificial muscles

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We here experimentally demonstrate artificial muscles that convert the energy of a high-energy-density fuel to mechanical energy. These muscles are fuel cells that in some embodiments store electrical charge and use changes in stored charge for mechanical actuation. The highest demonstrated actuator generated strains and mechanical output power densities are comparable to natural skeletal muscle, and the actuator generated stresses are over a hundred times higher than for natural skeletal muscle. Since the energy density of fuels like methanol is ~7.5 times higher than for advanced Li batteries, this advance seems quite important for such applications as autonomous robots or prosthetic limbs, where long operation without recharging or refueling is needed.

6168-63, Session 11

On the nature of dielectric elastomer actuators and its implications for their design

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Dielectric Elastomer (DE) actuators have been known widely. Under laboratory conditions, these actuators show promising performance. However their practical application has not been able to achieve their full potential. This paper summarizes the results of a detailed analytical and experimental study of the failure modes and performance boundaries of DE actuators whose objective is to establish fundamental design principles of successful DE actuators.

Continuum mechanics models of three fundamental DE failure modes (material strength, dielectric strength and pull-in) were studied in function of actuator film stretch rate and film pre-stretch. These analytical models suggest that DE actuators made with highly viscoelastic films are capable of reliably achieving relatively large extensions when actuated at high speeds (high stretch rates). The implication of the analysis is that DE actuators used in low speed applications such as slow continuous actuation are subject to failure at substantially lower extensions. Experimental results confirm these results.

The optimal DE actuator performance (force, work output per cycle, power and efficiency) was experimentally studied as function of actuator speed (stretch rate) and extension. These are relatively complex functions. Analytical models were developed to help understand the experimental results. These studies suggest that viscoelasticity and current leakage are governing phenomena for the performance of DE actuators in terms of specific force output and efficiency. An important conclusion of these studies is that actuator speeds and extensions for optimal performance can reduce actuator life. Hence DE actuator design requires careful balance of design trade offs between reliability and performance.

In summary, experimentally validated models of the physical mechanisms governing the failure and performance of DE actuators have been developed. These models provide an understanding of the fundamental strengths and limitations of DE actuators. Further, they can provide the basis for effective DE actuator design guidelines.

6168-64, Session 11

Sound radiation properties of electroactive polymer loudspeakers

R. Heydt, SRI International

Electroactive polymer film (EPF) loudspeakers based on dielectric elastomers have been demonstrated previously at SRI International. Dielectric elastomer loudspeakers have the advantages of very light weight and the ability to conform to any shape or surface. This makes them attractive as low-profile, surface-mounted speakers in rooms or automobile interiors, and for applications in active noise control. EPF loudspeaker performance depends on a number of mechanical factors such as speaker shape and mechanical biasing, as well electrical driving characteristics. This paper discusses important aspects of performance, including loudspeaker sound pressure level and directivity.

6168-65, Session 11

Hybrid IPMC/PVDF structure for simultaneous actuation and sensing

X. Tan, J. R. Malinak, Y. Shen, Z. Chen, N. Xi, Michigan State Univ.

Ionic Polymer-Metal Composites (IPMCs) are a class of promising electroactive polymers with numerous potential applications in biomedical devices, biomimetic robotics, and micromanipulation due to their large bending motion, low actuation voltage, resilience, and biocompatibility. In these applications, compact sensing schemes are often desired for feedback control of IPMC actuators. Self-sensing utilizing the inherent sensory capability of IPMCs is appealing, but it is challenging since the dynamics and nonlinearities render compensation with linear bridge circuits ineffective.

In this paper a novel sensing scheme for IPMC actuators is proposed by integrating an IPMC with a PVDF (polyvinylidene fluoride) thin film that serves as a built-in, highly sensitive sensing layer. The soft, thin PVDF layer would take very little space on an IPMC-enabled device and have a minimal impact on IPMC actuation performance. The paper discusses the development of the hybrid IPMC/PVDF structure, actuation performance evaluation and analysis, and signal processing algorithms to deal with the hysteresis nonlinearity in the PVDF sensor. The efficacy of the proposed simultaneous actuation/sensing scheme is demonstrated experimentally. Further details are provided next.

To construct the sensori-actuator, a PVDF film (28 microns thick) is bonded to an IPMC actuating beam (50 by 5 by 0.3 mm) using insulating epoxy. A PC equipped with DSpace ControlDesk is used to control the IPMC actuation signal and process the PVDF sensing signal. A precision instrumental charge amplifier is designed to convert the high impedance signal generated by the PVDF sensing film to a low impedance voltage suitable for measurement by the data acquisition system. A laser displacement sensor is used for calibration of the PVDF sensor and for validation of the sensing model. Experiments have shown that the amplifier can measure dynamic as well as quasi-static deformation of the IPMC/PVDF hybrid structure, and thus are suitable for a wide spectrum of actuation conditions.

Quantitative investigation is performed to study the impact of the additional sensing and insulation layers on IPMC actuation performance by comparing the deflection levels, under fixed actuation signals, before and after the PVDF sensing layer is added. It is found that the choice of insulating glue strongly affects the bonding quality and the mechanical properties of the overall structure. With appropriate epoxy, the degradation of bending performance is insignificant. A mathematical model based on the composite beam structure is further presented to elucidate the experimental results.

As a piezoelectric material, PVDF reveals strong hysteresis in its charge - stress relationship, especially under large bending motions. This is confirmed by applying a quasi-static, sinusoidal actuation signal (0.01 Hz) and comparing the phase shift between the actual bending (through laser sensor) and the PVDF output. The Preisach operator is then proposed to capture the piezoelectric hysteresis, and furthermore, an efficient inversion algorithm for the Preisach operator is used to extract the correct bending information from the PVDF output. The effectiveness of the IPMC/PVDF sensori-actuator is verified by examining its sensing capability under a rich set of actuation signals, and by feedback control experiments, where the laser sensor is used as an independent observer in both cases.

6168-50, Session 12

Smart glass based on elelctrochromic polymers

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As economy is highly growing in the worldly wide, energy is strongly demanded. Within limited energy in the earth, energy efficient devices or systems are urgently

required. In the next twenty years, several percent of all energy used in the United States will be 'consumed' by residential windows. As a result of these findings, research into reducing waste heat in residential and commercial buildings has become an important field. A promising technology, developed to face this challenge, is electrochromic or 'smart', switchable glass. These glass are capable of controlling the throughout of radiant energy, potentially greatly reducing the amount of electricity consumed by heating and air conditioning by allowing sun in during the winter and blocking it during the summer.

Smart glasses are categorized by trigger into three main areas, thermotropics, photochromics and electrochromics. Here is introduced a fast response and energy efficient electrochromic glass based on conjugated polymer and inorganic ion storage layer hybrid configured systems.

Electrochromic glass (window) is composed of five layers, a conductive transparent, an electrochromic active, an ion conductive, an ion storage and a second conductive transparent layer. Conjugated polymer, Poly[3,3-dimethyle-3,4-dihydro-2H-thieno[3,4-b][1,4]dioxepine] (PProDOT-Me2), was used as a blue electrochromic active layer and inorganic vanadium pentaoxide film was utilized as an ion storage layer. Two assembly methods were described corresponding to two types of electrolyte, gel and liquid electrolytes. Dimension of smart glass up to 12 x 20 inch was developed. UV curable sealant was applied for the sealing devices. Color changing or switching speed of 12 x 20 inch smart glass is less than 15 seconds under applied 1.5~2.0 voltage. Red and green color electrochromic polymers were developed lately and will be demonstrated. Multicolor, high contrast ratio, fast switching speed, long open circuit memory and durability are our study goals. User can control the degree of tint, which remains after the power is turned off (open circuit memory). No space consuming or dirt collecting shades, curtains or blinds are needed. Additional applications of the smart window, e.g. aircrafts and automobiles will be discussed as well.

6168-51, Session 12

Ultralow-modulus electrically conducting electrode materials

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This paper describes progress in the development of low modulus electrically conducting thin film and free-standing nanocomposite materials as electrodes for EAPAD and other mechanical actuators that undergo large displacements. We have fabricated such nanocomposites using a modified self-assembly process that combines multiple layers of electrically conducting nanoclusters and advanced polymers. This layer-by-layer synthesis approach allows direct control over the volume percentage of the conducting and polymer species, and thus modification of electrical conductivity percolation behavior. At loading percentages of the conducting nanoclusters, electrical conductivities on the order of 10-5 ohm cm are obtained. For these loading percentages and electrical conductivies, we have demonstrated modulus lower than 1 MPa, which is significantly lower than reported in prior work. These new materials also exhibit maximum strain before failure of as high as 1000% (ten time elongation) and good mechanical recovery when released. Such materials have potential use as electrodes on high displacement mechanical actuators due to their very low modulus, ability to experience large strains, and good mechanical recovery. These materials will be demonstrated as part of the EAPAD-in-Action session at the SMS Conference.

6168-52, Session 12

The electromechanical response and fracture toughness of ultrathin metal electrode coatings on elastomer substrates

O. N. Scott, H. Bart-Smith, M. R. Begley, M. H. Jones, Univ. of Virginia

This talk will present experimental and theoretical analyses of the electro-mechanical response of metal/elastomer multilayers and the mechanical response of the electrodes to an applied strain. A novel test has been devised to determine the relationship between the mechanical response of clamped elastomer membranes, coated on both sides with metal electrodes, and an applied electric field. The load-deflection response of the multilayers subjected to different voltages was measured using an instrumented spherical indenter having dimensions comparable to the freestanding span. The measurements are used with close-form solutions for membrane deflection to determine the effective plane-strain modulus of cracked multilayers and electrically induced in-plane strains. The experiments demonstrate that: (i) electrically induced strains vary with the square of the electric field, as expected from electrostatic models of parallel plate capacitors, (ii) the transverse stiffness of membranes can be controlled using applied electric fields, (iii) analytical models accurately predict the relationship between electrode crack spacing, layer properties and effective moduli. Finally, we estimate toughness of the sub-micron metal electrodes, using cracking models that relate crack spacing, imposed strain and the energy release rate governing channel crack formation.

6168-53, Session 12

Novel compliant electrodes based on platinum salt reduction

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Dielectric elastomer actuators (DEAs) undergo large mechanical deformations during actuation, so compliant electrodes - electrodes that maintain conductivity under axial strain and bending - are critical to their operation. DEAs currently utilize carbon grease for the compliant electrodes [1, 2]; however, because the carbon grease must be painted on the actuator, this proves disadvantageous for some applications. Thus, a new type of compliant electrode that allows more precise geometric control would be beneficial. Unfortunately, compliant electrodes cannot be produced by simply loading conductive particles into an elastomeric matrix because this substantially increases the Young's modulus when the loading exceeds the percolation threshold, making the electrodes non-compliant [3].

We have developed a compliant electrode based on the impregnation-reduction process used to form electrodes in ionic polymer-metal composites (IPMCs), but instead of an ion-exchange membrane, we employ a UV-curable acrylated urethane (3108, Loctite) [4]. The fabrication procedure consists of mixing a platinum salt into the elastomer precursor, curing the elastomer under ultraviolet light, and reducing the salt to platinum metal. Because the elastomeric matrix is a photopatternable adhesive, meso-scale electrodes of varying geometries can be formed by exposing the precursor/salt mixture through a mask.

The materials were mechanically and electrically tested. Above the percolation threshold of 8 vol% platinum salt, the conductivity is 1 S/cm. The modulus of unloaded 3108 is 18.6 MPa [5], and for platinum salt loadings up to 15 vol%, the Young's modulus remains less than 32 MPa. Furthermore, the material maintains electrical conductivity under axial strains of up to 40%. The effect of temperature and dispersing agents on the platinum reduction were also investigated.

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6168-54, Session 13

Active control of stiffness and damping of piezoelectric polymer films

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This paper investigates a method for actively controlling the stiffness and damping provided by piezoelectric films such as may be used to construct biomimetic skins on small aerial vehicles. The method being investigated is based on the idea of elastic control via piezoelectric coupling, and uses a pre-tunable electronic circuit in parallel with a polyvinilidene fluoride (PVDF) film. The focus of the current work is on a fundamental-level understanding of the elastic control method, and in particular, on theoretically and experimentally characterizing the degree of dissipation control possible with this method.

A method to use piezoelectric coupling to control material damping was reported by Date et al. in 2000. They connected an operational amplifier based "negative capacitance" circuit in parallel with a poled, electroded PVDF film and were able to select/adjust certain circuit parameters to vary the material damping and stiffness of the film. This work was extended by Mokry et al. (2003a, 2003b), who used a semi-circular PVDF film within a tube to alter the acoustic transmissivity of the film. Both groups observed that the effective stiffness and damping of the film could be varied over a significant range by appropriately setting the ratio of two resistors in the circuit.

Since both structural and acoustic loads are important in practice, the present work investigates the response of a PVDF strip both to mechanical excitation and to acoustic excitation. Frequency response (based on Fourier analysis) and direct

impulse response observations are used to characterize the strip behavior. The response of the strip is investigated with and without the negative impedance circuit in parallel, to determine the extent to which the circuit parameters can influence the structural dissipation as reflected in the frequency and impulse response observations for the strip. In addition, given the simplicity of the circuit and its crucial role in enabling a PVDF strip to function as a "programmable" damper, a simple network analysis is presented that clarifies the operation of the circuit and the relationship between the resistor ratio and the complex elastic modulus of the strip.

This paper discusses the theoretical and experimental work so far which shows encouraging improvements in the dissipation in response to structural loads. It is emphasized that the effect of elasticity control on the structural impulse response with the structure vibrating as a membrane has not been reported in the work cited. Furthermore, it is shown here that a more economical low-power control circuit can sufficiently alter the dissipation characteristics increased dissipation, and this observation could be potentially important in practical implementations.

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6168-55, Session 13

Protein-based microhydraulic transport for controllable actuation

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Plants have the ability to develop large mechanical force from chemical energy available with bio-fuels. The energy released by the cleavage of a terminal phosphate ion during the hydrolysis of a bio-fuel assists the transport of ions and fluids in cellular homeostasis. Materials that develop pressure and hence strain similar to the response of plants to an external stimuli are classified as nastic materials. Calculations for controlled actuation of an active material inspired by biological transport mechanism demonstrated the feasibility of developing such a material with actuation energy densities on the order of 100 kJ/m^3 by Leo et al. [2004] (Proceedings of IMECE-2004). The mathematical model for a simplified proof of concept actuator referred to as micro hydraulic actuator uses ion transporters extracted from plants reconstituted on a synthetic bilayer lipid membrane (BLM). Thermodynamic model of the concept actuator discussed in Leo et al. [2005] (Proceeding of SPIE Smart structures conference -2005) predicted the ability to develop 5 percent normalized deformation in thickness of the micro-hydraulic actuator.

Controlled fluid transport through AtSUT4} reconstituted on a 1-Palmitoyl-2-Oleoyl-sn-Glycero-3- [Phospho-L-Serine] (Sodium Salt) (POPS), 1-Palmitoyl-2-Oleoyl-sn-Glycero- 3-Phosphoethanolamine (POPE) BLM on lead silicate glass plate having an array of 50 um holes driven by proton gradient was demonstrated by Leo et al[2005] (Proceedings of IMECE-2005). Bulk fluid flux of 1.2 ul/min was observed for each microliter of SUT4 transporter protein mix reconstituted on the BLM. AtSUT4 (Proton-sucrose co-transporter from Arabidopsis thaliana) proteins were made available suspended in pH7 medim (16.6 mg/ml). The flux rate is observed to be dependent on the concentration of sucrose present in pH4 buffer. 10 ul/min flux of fluid is observed for 5 mM sucrose in the first 10 minutes. The observed flux scales linearly with BLM area for the same quantity of SUT4 reconstituted on the membrane. The flux increases with the amount of proteins reconstituted on the membrane. Our current work is to build upon the current result and drive transport using biological fuel - Adenosine triphosphate (ATP). We will present our results from the ATP-ase (bio-fuel) powered fluid transport where chemical energy stored in ATP is converted to fluid flux which will be used for controlled actuation in a micro-hydraulic actuator.

6168-56, Session 13

Spring roll dielectric elastomer actuators for a portable force feedback glove

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In this paper miniaturized spring roll linear dielectric elastomer actuators (diameter: 12 mm, length: 45 mm, weight: 8 g) for a portable force feedback glove are presented. The actuator's core consists of a telescope and a spiral spring, which is around the telescope. During the fabrication, pieces of acrylic elastomer films (VHB 4910, 3M(r)) were biaxially pre-stretched, coated with a mixture of graphite powder and silicone oil, and were then wrapped around the compressed spring core. Based on a partly automated manufacturing process the actuators were produced at Empa Dubendorf. A basic electromechanical model was employed to qualitatively find manufacturing parameters resulting in an improved actuator performance.

The force-displacement characteristics of the actuators were determined with passive uniaxial tensile tests and isometric tests under an activation with high voltage (0-3.5 kV). All above measurements were controlled via LabView(r).

The passive tensile tests showed a quasi-linear force-displacement behavior of the actuators. From the active isometric tests we observed that the measured pre-stretch loads decreased non-linearly as the applied voltage was increased. It held for different pre-stretch levels. Furthermore, in the whole voltage range these pre-stretch loads decreased more if the material was more pre-stretched. The maximum compressive blocking forces of the actuators, which can be effectively used for a force feedback device ranged from 1.47 to 7.2 N, while the maximum free-strains varied from 1 to 5 mm. These wide variances originated mainly from the deficiencies in the actuator's constructions, imperfect materials and imprecise manual works. As expected from the viscoelastic material behavior of the acrylic film, all measurements results exhibited a strong time-dependency. Additionally, the actuators showed a poor electromechanical durability.

Due to the required high voltages, electrical safety precautions for the user are also discussed in this paper. The electrical properties of the actuators were measured and the complete device-user system was modeled with Simulink(r). Various protective measures were recommended.

A demonstrator for the actuator was made, by which the user can feel the actuator generated force and stroke. In addition, a prototype for a force feedback glove was built, which practically showed its force feedback concept.

In the end, this paper concludes and discusses the achieved results, and the next steps in the development of spring roll dielectric elastomer actuators for a portable force feedback device.

6168-57, Session 13

Studying the performance of linearly contractile biomimetic actuators to actuate fingers of an artificial hand

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Even though, the work dealing with the fabrication, modeling, characterization and improvement of EAP based smart structures often called as artificial muscles have been intensified in recent years, the discussion about the biological plausibility of the produced devices and related work can be considered as less studied compared with those dealing with other aspects of these types of materails. In this work, we report the results of a performance analysis of three different types of linearly contractile bio-mimetic actuators. The dielectric EAP actuator, designed and produced by EMPA, the McKibben artificial pneumatic muscle, designed and produced by INSA de Toulouse and used for a number of other applications by the authors of this article, and two IPMC based linearly contractile actuator structures have been chosen as candidates to reproduce biological muscle like behavior. In the case of IPMC based linearly contractile actuators, two different types of structures based on two different actuation schemes made by IPMCs with different membrane thickness and with different active cations were tested in the aim of changing the actuation performance, and different ionic liquids having low volatility rates were employed as solvents in order to improve the ambient air actuation. We then compared these materials in actuating a mechanical 3 degree of freedom index finger which is designed to be used as a prototype finger for the construction of a 5 finger artificial hand. The experimental site is equipped by the three different types of power supplies (Low DC voltage, high DC voltage and compressed air) that are necessary to drive the three different types of actuators as well as by the force and displacement measurement devices. The performance analysis has not been limited to the comparison of the generic experimental results (i.e. to the comparison of force and displacement measurements obtained using only the different physical materials) but it also includes the antagonist actuation performance analysis of each type of actuators in reproducing the dy-

namic and cinematic values of a specific finger motion. We have chosen the motion of pushing on a spring studied in a previous work in which the force exerted on a spring, muscular activity (EMG) and cortico-motoneuronal cells activity recorded in monkeys had been reported. Moreover, an artificial neural network (MLP) structure was proposed in that work to reproduce the biological phenomenon realised between motor cortex and forearm muscles driving the fingers. A simulator that reproduces all measured parameters of the whole motion employing the models of the biological muscles relating the EMG activities to the exerted forces and realised displacements was first established and tested. The performance analysis of different EAP based structures was then performed by replacing the models of biological muscles with those of all EAP actuators used in this work which can be defined as the parametric transfer functions relating the powering source to the produced forces and displacements. The simulation results were finally compared with the experimental results.

6168-58, Session 13

The control of the IPMC actuators by non-trivial electric signals

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A typical IPMC consists of a thin (<0,5 mm) polymer membrane with metal electrodes plated on both faces. Usually certain co-polymers of teflon, as Nafion, Flemion, Aciplex, etc. are used. The polymer membrane is plated with some noble metal such as platinum or gold. IPMCs typically work in a wet environment and an ionic conductive liquid - usually water - plays an essential role in the principle of their work.

One method to study the behavior of IPMC actuators is to investigate their equivalent circuit. Several electrical models of IPMC are published in the literature. The most distinguished of them are the discrete electrical model of an IPMC actuator described by R. Kanno and S. Tadokoro and the elaborated model of IPMC described by M. Shahinpoor and K. Kim. However proposed models do not explain several effects if we control IPMC actuator by non-trivial shape electrical signals.

In current work we show that using such kind technique can reduce actuator power consumption several times. We also propose modified equivalent circuit which describes the situation

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6169-01, Session 1

PVPF control of piezoelectric tube scanners

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As in most applications of nanotechnology speed and precision are important requirements for getting good topographical maps of material surfaces using Scanning Tunneling Microscopes (STM) and Atomic Force Microscopes (AFM). Many STMs and AFMs use Piezoelectric tubes for scanning and positioning with nanometer resolution. In this work a piezoelectric tube of the type typically used in STMs and AFMs is considered. Scanning using this piezoelectric tube is hampered by the presence of a low-frequency resonance mode that is easily excited to produce unwanted vibrations. The presence of this low-frequency resonance mode restricts the scanning speed of the piezoelectric tube. Concept of a Positive Velocity and Position Feedback (PVPF) controller is introduced and designed to dampen the effect of the undesired first resonance mode. To achieve good precision specific control signals are designed for the closed loop system to track a raster pattern. Experimental results revel a significant damping of the resonance mode of interest, and consequently, a good tracking performance.

6169-02, Session 1

Adaptive control of a scaled model of an aircraft vertical tail

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Twin-tail fighters encounter severe fatigue failure due to high amplitude vibrations induced by the buffet loads at high angle of attack flight. Besides improving the mechanical design of the tail (passive control), active control system seems to be an attractive option to reduce the vibration. In this paper the application of adaptive control systems for vibration suppression of a scaled model of a typical vertical tail is studied.

A total of 24 Piezoceramic actuators were bonded to both sides of a flexible fin model and accelerometers were employed as sensors to form a smart fin in this study. Using the xPC TargetBox of MathWorks a real time hardware-in-the-loop system was created. Some of the piezoelements were used as disturbance generators to simulate the buffet loads and the rest were grouped properly in order to have individual mode control authority. A frequency range of 5-100 Hz was considered to cover the first three dynamic modes in this study. However, the critical modes of vibration were the first bending mode (1st mode) and the first tosional mode (2nd mode). Thus, the efforts were concentrated on controlling these modes effectively.

Adaptive feedforward and feedback control systems were designed and implemented successfully. Sine dwell, chirp, and random excitations were applied to the smart fin and the adaptive controllers were able to reduce the vibration significantly. System identification was done both on-line and off-line. Sine dwell experiments showed that the adaptive controller suppressed each individual mode without any spillover effect on the other modes. A broadband vibration suppression using two properly selected sets of piezoactuators under random and chirp disturbances was also investigated. Another pair of piezoactuators sets was employed as disturbance generator. The Multi-Input Multi-Output adaptive control system demonstrated successful vibration suppression in broadband frequencies particularly at the first two peaks (first two modes). Results showed the importance of piezoactuators grouping in controlling individual modal control under a broadband disturbance. Details of the adaptive control system design and implementation in addition to the experimental results will be presented in the full paper.

6169-03, Session 1

Electromagnetic films as lightweight actuators for active noise reduction

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Increasing industrialisation leads to growing noise exposure. Noise can not only make a person deaf at exposures of over 86 dB(A), but it also acts as a factor for stress and can raise systolic blood pressure. Additionally, it can be a factor in work accidents, both by masking warning signals, and by impeding concentration. In vehicle cabins, the noise control at low frequencies is difficult, because a lot of unwanted mass must be added. Therefore active noise control (also known as noise cancellation, active noise reduction (ANR) or anti-noise) is a good option. Herewith unwanted noise from a primary sound source can be reduced significantly by anti-noise generated from a secondary source.: At present commercial active noise reduction systems are using moving-coil loudspeakers as actuators. These actuators need a quite large built-in volume and they are not lightweight. Therefore the industrial application of ANR in vehicles is limited. To reduce these difficulties the use of flat loudspeakers made of electromagnetic films seems to be a promising approach. It is a precondition for the use of such new technologies within an ANR-system to have a basic understanding of the dynamic systems behaviour and the sound transmission behaviour of such a lightweight active component.: This paper describes the investigation of a flat panel speaker which is based on electrostatic loudspeaker technology. First of all the passive transmission properties have been measured in a test bed. The passive acoustic insulation has been analyzed and weak spots in the frequency response were discovered. Afterwards the flat panel speaker has been used as actuator in an ANR-System to support insulation at those frequencies. An adaptive filter (FxLMS) was adjusted to the panel and the reduction capabilities of a single-output system have been determined.

6169-04, Session 1

H-infinity controller design for structural damping

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This paper describes a multivariable controller design procedure that uses mixed-sensitivity H-infinity control theory. The design procedure is based on the assumption that structural noise can be modeled as entering a state-space system through a random input matrix. The design process starts with a full-order flexible state-space model that undergoes a frequency-weighted balanced truncation to obtain a reduced-order model with excellent low frequency matching. Weighting functions are then created to specify the desired frequency range for disturbance rejection and controller bandwidth. A structural noise input matrix is also designed to identify system modes where maximal damping is desired. An augmented plant is then assembled using the reduced-order model, weighting functions and structural noise input matrix to create a mixed-sensitivity configuration. A state-space controller is then realized using an H-infinity design algorithm.

A two-input, three-output, doubly cantilevered beam system provides a design example. A 174th-order, discrete-time, state-space model of the cantilevered beam system was used to generate a reduced 40th-order model. A 55th-order H-infinity controller was then designed with a controller bandwidth of approximately 300 Hz. This non-square modern controller uses feedback signals from two piezoelectric sensors, each collocated with one of two piezoelectric actuators, and one highly non-collocated accelerometer. The two piezoelectric actuators provide the control actuation. Frequency analysis and time-domain simulations are utilized to demonstrate the damping performance.

6169-06, Session 2

Improvement of sound quality for interior noise control using the piezoelectric smart structure

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In recent years, much research in the field of acoustics has focused on the reduction of a sound pressure level. In particular, shunted piezoelectric damping is frequently shown to demonstrate significant performance characteristics over conventional viscoelastic materials, e.g. lower weight with increased controllability. The performance of the shunted piezoelectric patches depends on the shunt circuit's elements, e.g. resistance, inductance and capacitance. Shunt circuit's tuning parameters are focused on the resonant frequency in general. Since it is hard to create a wanted sound quality, it is a simple drop of the peak frequency levels. In this study, a sound design method that characterized sound quality based on the psychoacoustics is proposed. Design of Experiments (DOE) is used to create several modified interior noise. According to this, frequency bands which are objective sound quality are decided by using the subjective sound quality analysis and sensitivity analysis. Selected objective frequencies are applied for tuning frequency of shunt circuit. Using the above process, we have modified a wanted interior noise that had characterized the sound quality.

6169-07, Session 2

Improved self-sensing method for semiactive vibration suppression

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An improved self-sensing method using piezoelectric actuators for semi-active vibration suppression is investigated. By using extended system equations, the method can be implemented with a Kalman filter instead of the conventional bridge circuit technique. This method is applicable to MDOF structures with multiple piezoelectric actuators.

So far, a great number of researches on self-sensing methods using piezoelectric actuators have been conducted, and the use of a bridge circuit connected to a piezoelectric actuator is a common approach. However, the high sensitivity of the bridge circuit to parameter variation is a serious drawback of this technique. According to Anderson et al., a mere 1 % variation in piezoelectric capacitance can make active self-sensing control systems unstable because of the imbalance of the bridge circuit.

In the semi-active method that we consider, a piezoelectric actuator was connected to a passive electric circuit having a switch, instead of the voltage supplier. The circuit switch is controlled to suppress the vibration of a structure. With most of the switching logics, electric current flows in the circuit only for a short time, and the circuit is open for most of the time. Though the method can suppress various vibrations, it still needs to have many sensors distributed across a structure. In contrast, the proposed self-sensing method uses extended system equations and a Kalman filter, instead of distributed sensors or bridge circuits. Compared with the conventional bridge circuit method, our self-sensing method has the following advantages. 1) The method can control multiple-mode vibrations by selectively suppressing vibration modes, because modal displacements and velocities can be estimated with the Kalman filter. The switching of the circuit is followed by the polarity of the control input that is calculated from the Kalman filter. Furthermore, sufficient modal information keeps the self-sensing control system away from the harmful influence of residual modes. With such a bang-bang type of the switching control, residual modes may be excited when controlled modes are suppressed by a method whose control input changes sharply. Therefore, the small influence of residual modes is an important factor on, especially, some flexible structures. 2) The method is much less sensitive to parameter variation, since a sensitive bridge circuit is no longer needed. This robustness provides a great advantage over the conventional method. 3) The method can control multiple actuators synthetically rather than independently, because it makes a reference to the control input based on an active control scheme.

To clarify these advantages, numerical simulations and experiments were conducted with a MDOF structure. The numerical simulations demonstrated that the self-sensing method worked well and had significant robustness against parameter variations. The experiments demonstrated that the proposed self-sensing method suppressed well not only single-mode vibration but also multiple-mode vibration of the actual structure. This self-sensing method and the results of this investigation are, in principle, applicable to other vibration suppression methods, as long as the electric current flows for a short period in a circuit connected to a piezoelectric actuator; for example, not only semi-active vibration suppression, but also hybrid active vibration suppression.

6169-08, Session 2

Numerical and experimental optimized shunted piezoelectric circuit damping turbomachine structures

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Turbomachine bladed disks are particularly vibration sensitive and their dynamic stability depends on aero-elastic coupling. Rotating parts can be heavily stressed and the induced vibration magnitudes have to remain low to make them also high-cycle-fatigue resistant.

These systems have to respond to severe requirements and the multi-field features make the design process realized step-by-step. Nowadays techniques achieve their maximum of state-of-the-art in design and manufacturing. The remaining ways to reach even better compressor performance are to push away these aerodynamic and aeroelastic limits. The proposed solution is to use devices able to reduce vibration after being clamped directly on the structure. Pure mechanical damping has been already tested but these techniques remain in fact complex in design. The difficulty of supplying in energy active actuators, as the components are aimed to be bonded on rotating structures, constrains also by using only auto-supplied devices. Halfway between passive and active design systems stands out shunted piezoelectric circuit damping.

To realize the study on complex turbomachine geometries, the presented technique develops a Craig and Bampton component mode synthesis method combining both mechanical and electrical coupling parameters. These reduced models are afterwards used to optimise electrically the shunted piezoelectric element and its localization. The results, verified experimentally, let suppose that vibrations can be reduced significantly when the shunted piezoelectric circuit is mounted on a real structure.

6169-09, Session 3

Model-based design of piezoelectric energy harvesting systems

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In the design process of energy harvesting systems based on piezoelectric elements, the most interesting question is the achievable energy output. To estimate this amount a priori manufacturing of prototypes, a mathematical model is very helpful. Within this contribution we will introduce a model based on electro-mechanical circuit theory. Its parameters are identified by measurements and the model is validated by comparison to experimental results.

The model is designed to support the development-engineer in the dimensioning of energy harvesting units to specific application demands. Two main challenges in device design are investigated with the mathematical model: influence of the ambient excitation frequency, and influence of the load impedance.

Typically, the equivalent model approach delivers models for piezoelectric elements that are driven in resonance by electrical excitation. In the case of energy harvesting the piezoelectric elements are excited mechanically and most often non-resonant. Thus, we first set up a mechanical equivalent model for base excited systems. In first approximation it represents an energy harvesting unit around one resonance frequency. The model is expandable for a wider frequency range using the super positioning of multiple circuits.

From the viewpoint of optimum energy transformation between mechanical and electrical energy it is favorable to drive piezoelectric elements at resonance or anti-resonance. Thus, an energy harvesting system should be tuned to the excitation frequency. Therefore, the model is extended by an additional mass parameter which makes it possible to match the resonance frequency of the energy harvesting system.

The method to archive the models parameters is described in detail. For each considered resonance frequency a small range admittance measurement is done. Using this data, an analysis is done where an algorithmic procedure performs the process of identifying of the modal parameters.

To validate the results of the mathematical approach, measurements of the power output of energy harvesting systems have been done. With an automated measurement set up. Several piezoelectric elements have been studied in a wide area of different loads and frequencies with this test bench. Experimental results are analyzed to show the model's area of validity and investigate the behavior of the energy harvesting system outside of this area. Further, the influence of an additional mass on the maximal output power is examined and crosschecked with the modeled data.

Our model allows for the systematic design of piezo-based energy harvesting systems that optimally match specific applications. By optionally tuning the energy harvesting system for a given electrical load and matching the resonance frequency to the excitation frequency given by the environment, the power output of the system can be maximized.

6169-10, Session 3

Tunable resonant frequency power harvesting devices

W. Wu, Y. Chen, B. Lee, J. He, National Taiwan Univ. (Taiwan)

Over the past years, there has been growing interests in the field of power harvesting technologies for low-power electronic devices such as wireless sensor networks and biomedical sensor applications. Methodologies of using piezoelectricity to convert mechanical power of vibrating a cantilever beam which was excited by external environmental vibration to electric power were widely discussed and examined. As operating in resonant mode of the cantilever beam was found to be the most efficient power harvesting condition, but in most cases that the resonant frequencies of the cantilever beam are hardly matching with the frequency of external vibration sources. The mechanical resonance has relatively high Q factor, and thus the harvesting output will be significantly lower compared to the condition when resonance matching to external vibration frequency. A tunable resonant frequency power harvesting device in cantilever beam form which will shift its resonant frequency to match that of the external vibrations will be developed and verified in this paper. This system comprises a variable capacitive load to shift the gain curve of the cantilever beam and a low power microprocessor will

sampling the external frequency and adjust the capacitive load to match external vibration frequency in real-time. The underlying design thoughts, methods developed, and preliminary experimental results will be presented. Potential applications of this newly developed power harvesting to wireless sensor network will also be detailed.

6169-11, Session 3

MEMS generator of power harvesting by vibrations using piezoelectric cantilever beam with digitate electrode

B. Lee, J. He, W. Wu, W. Shih, National Taiwan Univ. (Taiwan)

Of all possible energy sources, the mechanical vibrations have been considered a potential choice for power harvesting in a wide variety of applications. This paper presents the development of a piezoelectric MEMS generator which has the ability to scavenge mechanical energy of ambient vibrations from their surroundings and transform it into electrical energy that can be used in energy storage applications. The piezoelectric MEMS generator comprises a beam structure based on the silicon wafer, and the digitate electrode placed in between the upper and the lower laminated lead zirconate titanate (Pb(Zr,Ti)O3, PZT) material, to transform mechanical strain energy into electrical charge with using the d33 mode of PZT. A proof mass is built at the bottom plate of the beam, to adjust the structure resonant frequency of the piezoelectric MEMS generator, for most adaptable frequency matching to the ambient vibration of its surroundings. Different beam shapes are also examined to vary the strain energy density distributions on the beam structure of the piezoelectric MEMS generator and identify the characteristics of the relations between the beam shape and the energy harvesting ability. To improve the piezoelectric MEMS generator fabrication process, a self-made PZT deposition chamber which could deposit PZT thin film up to microns in minutes was used to deposit the piezoelectric layer on the beam structure of the piezoelectric MEMS generator. A feasibility study of the piezoelectric MEMS generator is performed and the test results obtained from harvesting energy through mechanical vibrations will also be presented.

6169-12, Session 3

Harvesting vibration energy for self-powered piezoelectric sensors

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Piezoelectric materials can be used as sensors for monitoring structural vibrations. At the same time, piezoelectric materials can also convert the mechanical energy under the vibration environment into electrical energy and thus can be used as power generators. Therefore, using piezoelectric elements to sense and harvest energy concurrently could be very attractive in nowadays structural health monitoring, especially when wireless sensor networks are utilized in the system. In this research, a novel operating scheme for a self-powered piezoelectric sensor is studied, in which one piece of piezoelectric element will be simultaneously used as a sensor and a power generator under vibration environment. An ultra-low power microcontroller is used in the system for receiving and conditioning the signals from the sensor for further processing, for example, wireless transmission. The microcontroller also adjusts a DC-DC switching converter, which is applied in the harvesting circuit to enhance the energy harvesting efficiency. The harvested energy is stored in the energy storage device, a rechargeable battery, to operate the microcontroller and the system as a whole. Experimental efforts are carried out to implement the integrated system. The results of this study show the feasibility of a self-powered piezoelectric sensor that could be utilized in structural health monitoring.

6169-13, Session 3

Energy harvesting from mechanical vibrations using piezoelectric cantilever beams

T. J. Johnson, D. Charnegie, W. W. Clark, Univ. of Pittsburgh

In this paper, a design methodology for an energy harvesting device will be investigated and results will be presented to validate the design. The energy harvesting device in the study will be a piezoelectric cantilever beam used to convert mechanical vibration energy into a useful electrical energy source. While the study of cantilever beams as energy harvesting devices is not new, previous studies have taken a different approach to the design methodology. Those studies primarily focused on designing a device and testing it by driving it through a certain frequency range to determine how much energy it could produce.

In this our study, we will take a different approach to designing the energy harvesting device. We start with known vibration data, frequency and vibration amplitudes from a specific application. We also have a know power requirement that the energy harvesting device must meet. Then from the given vibration data, we find a range of frequency within the given data where the energy harvesting device will generate the required energy to meet the power requirements. The device is then designed specifically targeting that frequency range. This approach is presented as part of a more general approach to designing energy harvesters for any application.

6169-14, Session 4

Phase control of a magneto-rheological tuned vibration absorber

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This paper presents a development of a control law for a Magneto-Rheological Tuned Vibration Absorber (MRTVA) and evaluates the dynamic performance of the MRTVA with the control. It considers a single-degree-of freedom structure model coupled with an MRTVA. The MRTVA is a semi-active TVA that employs an MR damper as its damping element. To model the MR damper in the TVA, we used the Bouc-Wen model. Using the model, we developed a control law that is based on the phase angles between the structure and the TVA masses. The objective of the controller was to keep +/- 90 degree phase condition, ensuring the maximum performance of the TVA in counteracting the motions of the structure mass. After obtaining the optimal tuning system parameters, we performed parametric study of the system by varying the mass, the stiffness, and the damping of the structure. Moreover, we compared the dynamic performance of the MRTVA (with the phase control) with the equivalent passive system as well as other control methods (such as skyhook control).

6169-15, Session 4

Seismic protection of civil historical structures by MR dampers

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The use of structural control systems for seismic protection of structures represents a relative new area of research that is growing rapidly. A wide variety of devices is now available, ranging from relatively simple passive dampers and isolators to complicate active systems with actuators, sensors, and digital controllers.

Passive systems represent a reliable and satisfactory way to protect civil structures from seismic action used in many worldwide applications. A limit of this technique is the lack of adaptability to changes in external loading. Alternatively, active structural control systems are available, using high performance sensors and actuators digitally controlled by specific algorithm derived from optimal control theory. However, active systems are more complex and expensive, less reliable than passive systems and may require relatively large external power supplies. These factors limit their use in seismic protection applications.

The aim to obtain an effective, reliable and not too expensive structural control system can be reach using smart devices: these are very similar to passives, but have the important difference to be controlled in real time, modifying the produced control forces changing their mechanical properties.

Magnetorheological (MR) dampers are one of the best examples of smart devices, due to their ability to dissipate energy and their low power requirements. They are based on the use of magnetorheological fluids, which are suspension of micron-sized magnetizable particles in an appropriate carrier liquid, able to reversibly change from free flowing, linear viscous liquids to semisolids having a controllable yield strength (100 kPa order) in milliseconds when exposed to a magnetic field.

MR dampers are very suitable in the semi-active control application in civil structure, thank to their characteristics: reaction force full controllable in dynamic range, simple mechanics and low power supply.

The aim of the work is the evaluation of the effectiveness of a vibration control system based on MR dampers, in the case of a typical Italian historical construction under seismic action. The reference model has been extracted from the structural scheme of a long-bay building and the control strategy takes into account a mass damper system.

The MRF damper design has been dealt with, by considering mechanical, hydraulic and electronic related aspects and problems. Both static (i.e. locking force) and dynamic (i.e. max damper speed, energy dissipation) performance of the device have been predicted by means of theoretic and numerical models.

A specific logical scheme of the building integrated with the MRF device has been realised by means of the Simulink toolbox. The effects coming from the MRF activation have been simulated by imposing suitable control laws to related damp-

ing parameters of the scheme.

By taking advantage of this model, the performance of the semi-active control system has been evaluated in comparison with the passive control strategy and the structure without control.

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6169-16, Session 4

A 6-DOF model of magnetorheological vibration isolation system for hydraulic hybrid vehicles

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This paper presents the results of vibration isolation analysis for the pump/motor component of hydraulic hybrid vehicles (HHV). The HHV are designed to combine gasoline/diesel engine and hydraulic power. Electric hybrid technology is being applied to passenger cars with small and medium engines to improve the fuel economy. However, for heavy duty vehicles such as trucks, buses which requires much more power, the hydraulic subsystem is more efficient than the electric one in providing regenerative power. In function, the hydraulic hybrid subsystem can potentially improve the fuel efficiency of the vehicle by recovering some of the energy that is otherwise wasted in friction brakes. In braking process, the driveshaft is engaged to the hydraulic subsystem, and the fluid is pumped from low pressure accumulator to high pressure accumulator where it is stored. When the brake is released, the high pressured hydraulic fluid, flowing from high to low pressure accumulator, “assists” the engine in the initial acceleration period. Dual functional pump/motors are the main components of the HHVs. These devices which function as pumps while capturing the kinetic energy of the vehicle can also generate torque while they work as a hydraulic motor releasing the energy. Since the main component of the subsystem always involves with rotating parts and moving fluid in its operation, noise and vibration are an issue that affects the ride comfort of both passengers and surrounding people. This study looks into the possibility of reducing the transmitted noise and vibration from the hydraulic subsystem to the vehicle’s chassis by using smart magnetorheological (MR) dampers. MR dampers utilize MR fluid which is made of pure iron particles suspended in a carrier fluid. Under the effect from applied magnetic field, the particles form chains parallel to the field. These chains resist the motion of the fluid in perpendicular direction. The chains also make the MR fluids become semi-solid which can deliver variable yield stresses depending upon the magnitude of the applied magnetic field. To this end, the pump/motor is modeled as a six degree of freedom (6-DOF) rigid body. Its mass and inertia properties are inherited from the real pump/motor used in the hydraulic subsystem. A 6-DOF isolation system, consisting of four mounts connected to the pump/motor at four different points, is modeled and simulated. The mount is designed with the combination of regular elastomer component and MR damper. In the simulation, the real loading and working conditions of the pump/motor are considered. Therefore, the effects of both shock and vibration are analyzed. The transmissibility of the isolation system is monitored in a wide range of frequency. The geometry of the isolation system is considered in order to sustain the weight of the hydraulic system without affecting the design of the chassis and the effectiveness of the vibration isolating ability. A control method is is studied for the isolation system to respond the fastest and most effectively to the vibrational conditions. The simulation results are then compared with the performance of the isolation system made of regular elastomer to shown the advanced achievement of the system with integrated MR damper in reducing the vibration for different working cycles of the regenerative system.

6169-17, Session 4

Semiactive control using magneto-rheological dampers for payload launch vibration isolation

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The most severe mechanical environment in the lifetime of a satellite occurs during its ascent into orbit. To ensure the payload survivability, heavy procedures of design, experimental tests and simulation of launcher/payload coupling have to be carried out, which increases duration and cost of flight qualification. The isolation of the payload from 5 Hz upwards would avoid such procedures, while enhancing the vibratory comfort of the spacecraft. Over the past years, some passive soft isolation systems have been investigated, where dissipative elements were used to damp the suspension modes. The concept of soft mount is very attractive but, in its passive version, is submitted to an inherent trade-off on the choice of damping. In order to avoid such a trade-off, we can resort to the use of actuators or adaptive passive elements instead of passive elements. In this work, a soft interface between the launcher and the payload using Magneto-Rheological dampers is investigated. Because of their high dynamic range, large force and stroke capacity and low power requirements, these devices seems to be good contenders to launch constraints, in contrast to other smart materials.

The results reported here concern essentially two configurations of semi-active isolation system: the single axis and the 6 degrees of freedom configurations. The study of the single axis system has enabled one to draw some conclusions on the lay out of the isolation system and on the design of the semi-active controller. A limitation of isolation performance in high frequency is due to the minimum damping force at zero current while another limitation in low frequency exists because of the maximum damping force. As a consequence, the effort range of the damper has to be optimized for both low and high frequencies. As regards the semi-active controller design, in the single dof isolation system, a clipped continuous skyhook damper control using PI control to track the desired force was found to be efficient. Simulation as well as experimental results show that, while requiring few energy, a semi-active isolation system using a MR damper has the ability to approach the performance of a soft active isolation system, especially for narrow band disturbances. For broadband disturbances, the performance is then slightly deteriorated and may require some modifications of the controller, such as the introduction of a threshold in the clipping strategy.

Finally are reported the first conclusions on the semi-active hexapod isolation system. A design analysis on the geometrical configuration was carried out in order to minimize the coupling effects between the struts, while trying to have low frequency axial, lateral and rocking modes to isolate in all the directions. An experimental equipment issued from this analysis has been built to verify the simulation results. A multi-SISO control approach is adopted, but due to inevitable couplings between the struts, MIMO control using modern approaches such as LQG will be considered as well.

6169-18, Session 4

An experimental study of MR fluid dampers for vibration control of one offshore structure

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The possibility of reducing offshore structural response under strong external excitations such as wind storm, sea ice and earthquake via control systems is attracting the interest of a large number of researchers. Up to now, lots of dampers have been installed on different offshore structures. As one new kind of effective semi-active device, magnetorheological (MR) fluid damper has been used in the field of mechanical equipment, automobile and civil construction, however, the practical application for vibration control of offshore structure has not seen before. In this paper, 8 MR fluid dampers with maximum damping force of 100kN for vibration control of one offshore structure with total weight of 650t have been developed and tested. The general situation of MRF damper system and the offshore structure include manufacturing issues, powering, range of variability of the mechanical parameters and response time are introduced.

6169-19, Session 4

Magnetorheological fluid (MRF) flow in channels with MRF impregnated porous walls

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This work focuses on the how the pressure drop and the induced wall shear stress of magneto-rheological fluids (MRFs) are affected in channel flow, where the channel walls are stainless steel porous surfaces impregnated with MRF. The porous walls

are impregnated such that there is no flow through the porous media. Several different porosity sizes and two different impregnation techniques are utilized in this study. The pressure drop vs. the volumetric flow rate data are plotted for each porosity and impregnation technique. For comparison, the MRF pressure drop in porous walled channels is normalized by the MRF pressure drop in channel with smooth surface without porosities. From these analyzes, it has been shown that under an applied magnetic field, the impregnated porous wall surface would increase the MRF pressure drop significantly when compared to the smooth surface. It is also concluded that the impregnation technique affects the amount of iron particles trapped inside the porosities, therefore affect the pressure drop. The study revealed that, the impregnation technique, as well as the porosity size, affect the amount of iron particles trapped inside the porosities, therefore affect the overall pressure drop. The pressure drop can be increased by 65% without changing the channel size and MR fluid properties. The surface properties of the channel greatly affect the pressure drop.

6169-20, Session 4

Theoretical and experimental investigation into dynamics characteristics of a rotor supported on a disk-type

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The rheological properties of magneto-rheological (MR) fluid can be dramatically and reversibly changed by the application of an external magnetic field, a disk-type MR fluid damper based on shear mode was developed and it was shown that the dynamic characteristics of the disk-type MR fluid damper are controlled by a low-voltage electromagnetic coil and that the disk-type MR fluid damper can effectively attenuate the rotor vibration. In this paper, the dynamic characteristics of the disk-type MR fluid damper are studied experimentally and theoretically in a flexible rotor with an over-hung disk. The effects of the applied currents, rotor imbalances and different fraction MR fluids on the rotor imbalance response are systemically studied. The experimental results are basic in agreement with theoretical ones obtained by the Bingham fluid model, but the differences are also analyzed. It is shown that the dynamic behavior of the disk-type MR fluid damper can vary with the applied current. There is a break-loose phenomenon in the unbalance response curve of the damper. The break-loose speed rotational speed of the damper, below which the damper does not move, depends on the rotor imbalance, applied current and property of the MR fluid. The higher the applied current, or the more the magnetizable particles in the MR fluid or the smaller the rotor imbalance, the higher the break-loose rotational speed of the damper will be. The dynamic characteristics of the disk-type MR fluid damper filled with a high weight percentage MR fluid or with higher applied current behave as a system with a softening force.

6169-21, Session 4

Experimental investigation on the effectiveness of a magneto-rheological fluid squeeze film damper

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The squeeze film damper (SFD) is one of most effective methods of applying external damping to the rotor system of high-speed rotating machinery, because of both its relative constructional simplicity and its effectiveness in attenuating rotor vibration and transmitted force in the properly designed cases. The characteristics of the conventional SFD is highly non-linear in the range of high journal eccentricity ratios and cannot be controlled easily on-line according with the different operating conditions of rotor, especially when the rotor passes through several critical speeds, the effectiveness of SFD in both attenuating rotor vibrations and transmitted force is, therefore, limited.

In order to improve the controllability of traditional SFD characteristics, we use magneto-rheological(MR) fluids with rapid, reversible and dramatic change in its apparent viscosity by an external magnetic field to develop a controllable MR fluid SFD. A rotor test rig with MR fluid SFD is built in order to demonstrate the effectiveness of the MR fluid SFD in attenuating the rotor vibrations. In this paper, we first describe the concept and structure of the controllable MR fluid SFD and the rotor test rig, then study the dynamic behaviour of the MR fluid SFD for attenuating rotor vibration and the effectiveness of the semi-active control on the rotor vibration by the MR fluid SFD. It is shown that the dynamic characteristics of the MR fluid SFD can be easily controlled and the MR fluid SFD is very effective for control of the rotor vibrations if the MR fluid with the relatively low initial viscosity and sensitivity to the low magnetic flux is used.

6169-22, Session 5

Frequency and temperature effects on damping properties of TbxDy1-xFe2 particulate composites

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Mechanical energy absorption characteristics of polymer matrix Terfenol-D particulate composites have been experimentally measured. In this work composites were manufactured with varying particle Terbium concentrations (TbxDy1-xFe2) and constant volume fraction (45%). Applications of tensive and compressive loads result in significant energy absorption through domain wall motion. Increasing strain amplitudes (0 to 3500 microstrain) increases the damping capacity while simultaneously decreasing the elastic modulus. Measured values of tan δ vary from 0.02 to 0.10 depending of strain amplitude. Corresponding elastic modulus varied from 6 to 11GPa. The effect of frequency variation as well as temperature variation on the composites is experimentally evaluated. Results indicate low dependence on either temperature or frequency within measured ranges.

6169-23, Session 5

Modeling of air viscous damping in MEMS devices

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In this paper, the air viscous damping in MEMS microbeams is modeled analytically and compared with experimental results. For vibrating MEMS devices, the airflow force is the most important factor influencing the air viscous damping. This force has two mechanisms: force in the narrow gap and force in the free space. The former is known as squeeze-film damping and the latter as airflow damping. The squeeze-film damping for a solid and straight vibrating cantilever beam is analyzed using the well-known Reynold's equation. The expression is then modified to include the effects of release etch-holes and initial curled-shape of the microbeams due to fabrication and inherent film stress gradients. The airflow damping, caused by the air surrounding the cantilever beam, is determined by solving a modified form of the Navier-Stokes equation using the bead model, which is derived based on the oscillation of a string of spheres (beads).

To investigate the air viscous damping effects on vibrating micro cantilever beams a simple laser interferometric technique is used. A microcavity is formed between the substrate and a top thin film structure in the form of a cantilever beam. Its fabrication is simple requiring only two masks. When affixed to a vibrating surface, the amplitude and frequency of vibration are determined by illuminating the beam with a monochromatic light source and analyzing the back reflected light to determine deflection of the beam with respect to the substrate. Because the thin film cantilever beam and the substrate are approximately parallel, this convenient two-mirror cavity arrangement needs no alignment, no reference arm, and no sophisticated stabilization techniques. The magnitudes of the relative displacements of the beam with respect to the substrate are strongly affected by air viscous damping (a result of the squeeze film damping in the cavity and the free air damping on the other side of the cantilever). Different widths, cavity thicknesses, and release etch-holes affect the air viscous damping.

This paper introduces a closed-form expression considering air viscous damping effects to accurately predict the dynamic response of microbeams used in MEMS devices such as accelerometers, gyroscopes, switches, and micromirrors. The closed-form solution is compared against experimental data gathered during the dynamic characterization of micro cantilever beams with different widths, air gaps and release etch-holes. By comparing the measured results to those generated by analytical models, we demonstrate that they match the damping coefficient to within 10%. Finally, the guidelines of using this modeling for typical MEMS devices are also provided.

6169-24, Session 5

Vibration control of beams using constrained layer damping with functionally graded viscoelastic cores: theory and experiments

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Conventionally, the viscoelastic cores of Constrained Layer Damping (CLD) treatments are made of materials that have uniform shear modulus. Under such conditions, it is well-recognized that these treatments are only effective near their edges where the shear strains attain their highest values. In order to enhance the damping characteristics of the CLD treatments, we propose to manufacture the viscoelastic cores from functionally graded materials (FGM) that have optimally selected gradient of the shear modulus over the length of the treatments. With such optimized distribution of the shear modulus, the shear strain can be enhanced, and the energy dissipation can be maximized.

The theory governing the vibration of beams treated with CLD, that has functionally graded viscoelastic cores, is presented using a spectral finite element (SFE) approach. The predictions of the SFE model are validated experimentally for plain beams, beams treated conventional CLD, and beams with CLD/FGM of different configurations.

The obtained results indicate a close agreement between theory and experiments. Furthermore, the obtained results demonstrate the effectiveness of the new class of CLD with functionally graded cores in enhancing the energy dissipation over the conventional CLD over a broad frequency band.

Extension of the proposed one-dimensional FG/CLD to more complex structures is a natural extension to the present study.

6169-25, Session 5

Damping added to floors by seated crowds of people

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There is a trend to build floors in stadia and in office buildings with span lengths so long that floor dynamic characteristics become parameters that need to be considered in floor design. The assessment of floor damping is an essential task in the evaluation of the dynamic performance of a floor as it has significant impact on floor vibration levels, and this paper explores the not well understood relationship between floor damping and humans sitting on a floor. The origin to problematic floor vibrations may be humans in motion (jumping, dancing or walking) on the floor, but often a seated crowd of people is also present such as on a grandstand or in an office building. Ultimately, the action of humans jumping can jeopardize structural safety (e.g. on grandstands), but even less intensive human action can be problematic as floor accelerations may reach levels that are discomforting to the seated crowd of people.

The seated (stationary) crowd is interesting. Firstly, because the people within the crowd may perceive floor vibrations as annoying, but secondly because the presence of the crowd on the floor will also significantly influence floor damping as demonstrated in the paper. The crowd itself thus has a bearing on the vibration exposure of people within the crowd, and on floor safety for that matter. It is therefore essential to be able to model how the crowd influences floor dynamic characteristics, and floor damping especially.

The paper contributes by presenting results of controlled experimental investigations that involved humans sitting on a vibrating test floor. In tests, floor damping and frequency were identified for various sizes of the human crowd. On basis of the experimental investigations it is investigated whether the human crowd can be represented by an auxiliary system attached to the vibrating floor mass. This would imply dynamic interaction between the crowd mass and the floor mass and the paper evaluates the applicability of a two-degree-of-freedom human-structure interaction model in describing the recorded dynamic characteristics of the human-occupied floor. Useful estimates of the parameters of the human-structure interaction model are identified by calibration.

The paper describes the tests and the modal identification procedures. Additionally, the methodologies adopted for evaluating and updating the human-structure interaction model are outlined. As for the results of the updated dynamic model of the human-floor system, comparison is made with research results obtained by others and the recorded floor dynamic characteristics (frequency and damping) are compared with the model predictions of the simple added mass model of humans. The last-mentioned model is that normally adopted for seated crowds of people for static calculations.

Since the approach of considering modelling a crowd of people as an auxiliary attachment system to a floor is rather novel, the paper also addresses some of the implications of this modelling approach and thus of the increase in floor damping added by humans. Overall the results of the updated human-floor interaction model imply that the damping added to a floor by a seated crowd of people would be significant for any dynamic calculation of floor vibration.

6169-26, Session 5

Smart damper designed with magnetostrictive materials

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Increasing research efforts have been devoted in recent years to the development of new controllable dampers for mechanical equipment, automobile and civil construction, in the aim of mitigating vibration of above structures during normal service condition or wind storm and earthquake. Most of the new controllable dampers are made with special performance of smart materials, such as MR/ER fluid, piezoelectric ceramic and shape memory alloy. Although has similar smart performance such as rapid response time, low power requirement and large driving force with those smart materials, magnetostrictive material is only got attention by a few researchers. In this paper, by analysis character of magnetosrtrictive effect, the possible dampers such as smart friction or viscous dampers may be made with magnetosrtrictive material are discussed. The influence effect of structural parameters on performance of above dampers is studied.

6169-27, Session 5

Vibration control of beams using stand-off layer damping: finite element modeling and experiments

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Damping treatments with stand-off layer (SOL) have been widely accepted as an attractive alternative to conventional constrained layer damping (CLD) treatments. Such an acceptance stems from the fact that the SOL, which is simply a slotted spacer layer sandwiched between the viscoelastic layer and the base structure, acts as a strain magnifier that considerably amplifies the shear strain and hence the energy dissipation characteristics of the viscoelastic layer. Accordingly, more effective vibration suppression can be achieved by using SOL as compared to employing CLD.

In this paper, a comprehensive finite element model of the stand-off layer constrained damping treatment is developed. The model accounts for the geometrical and physical parameters of the slotted SOL, the viscoelastic, layer the constraining layer, and the base structure. The predictions of the developed model are validated against the predictions of the commercial finite element code ANSYS. Furthermore, the theoretical predictions are validated experimentally for SOL treatments of different configurations.

The obtained results indicate a close agreement between theory and experiments. Furthermore, the obtained results demonstrate the effectiveness of the CLD with SOL in enhancing the energy dissipation as compared to the conventional CLD.

Extension of the proposed one-dimensional CLD with SOL to more complex structures is a natural extension to the present study.

6169-28, Session 5

Granular damping analysis using Monte Carlo approach

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Granular damping is realized by inserting granules/particles of various shapes, sizes, and materials into enclosures attached to or embedded in a structure. The underlying principle for granular damping is to absorb and dissipate vibration energy through particle-to-wall and particle-to-particle frictional collisions. Certain materials can sustain very high temperature and remain at granular status to effectively provide passive damping. Therefore, granular damping has unique advantage for harsh environment applications. Currently, the numerical analysis of granular damping is based on discrete element method (DEM) where Newtonian equations of motion for all involved granules are integrated for the characterization of granular motion. While straightforward and accurate, this approach is computationally costly, which leads to difficulties in both analysis and design. In this paper, we will develop an improved Mote Carlo based statistical approach specifically for granular damping analysis.

The advantage of general Monte Carlo approach is that one does not need to perform contact examination, which leads to reduction in computational cost. This, however, will result in unrealistic granular volume density in certain regions in granular vibration analysis. That is, certain regions could have unrealistically large number of granules. Moreover, since granular contacts are not tracked, the impact/friction effect of granules acting on the enclosure cannot be calculated. In this research an innovative approach will be developed to tackle these issues. While the individual granular contacts will not be examined to reduce computational time/cost, the granular damper will be divided into cells and cell population will be constantly checked to prevent the occurrence of over-population. In the meantime, the momentum exchange between granules and “full” cells will be taken into account through contact mechanics analysis. The impact/friction on the enclosure/structure will be calculated by analyzing overlapping/contact between the vibrating enclosure and the cells that are adjacent to the enclosure walls. With these improvements, the Improved Monte Carlo simulation will then be coupled to structural analysis for damping evaluation. Detailed numerical analyses are performed to highlight the efficiency and accuracy of the proposed new approach. Using this new algorithm, we carry out parametric analysis on granular damping to obtain guidelines for system optimization.

6169-29, Session 5

Dynamic behavior and damping capacity of auxetic foam pads

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In this work we describe the viscoelastic properties and dynamic characteristics of a sets of damping pads made out auxetic PU-PE foams. The primary applications targeted are antivibration gloves, damping mats and high structural integrity packaging. The viscoleastic properties at room temperature and frequency range up to 500 Hz are obtained identifying the equivalent complex modulus of the foams from a BSI transmissibility test. The transmissibility of the various auxetic foams is decreased by 30 % on average compared to the conventional foam base. The energy capacity at higher dynamic strains is measured at low frequency (5 Hz) for structural integity applications up to 100000 cycles. In this case, the auxetic foams show a damping capacity factor in terms of dissipated energy per unit volume with a 15-times increase compared to the conventional foams at different loading ratios. We also show results related to auxetic foams doped with MRF fluid for active vibration control pads, with analysis of time constants in actuations induced by external constant flux magnetic fields. and

6169-30, Session 5

Investigations on the development of a mixed displacement-pressure formulation for an anelastic displacement field finite element

R. Rusovici, Florida Institute of Technology

Space and weapon delivery systems contain guidance components and payload that need to be protected from the extremely harsh acoustic excitation present during launch operations. The above example represents just one application where high-damping viscoelastic materials are used in the design of shock and vibration isolation components. The shock transients generally encountered are characterized by a broad frequency spectrum. Widely-available commercial finite element codes do not offer the proper tools to model the frequency-dependent mechanical properties of viscoelastic materials over the frequency domain of interest. An added difficulty is the large Poissson's ratio exhibited by some of these materials, which indicates that previously developed displacement-based finite element formulations should be complemented with mixed pressure-displacement finite element formulations. The Anelastic Displacement Fields (ADF) method is employed herein to model frequency-dependence of material properties within a time-domain finite element framework and using a mixed displacement-pressure finite element formulation. Solid finite elements based on this new formulation are developed and validated. Model predictions are compared against theory and experiment.

6169-31, Session 5

The analysis of distributed systems with nonlocal damping

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The dynamic response analysis of damped structures is important in many areas of mechanical, civil and aerospace engineering, such as the vibration isolation of precise equipment, aircraft noise, or the vibration of cable stayed bridges. Although the damping model plays a key role in the dynamic analysis, particularly for complex structures, this model is often approximated by classical or proportional damping distributions for convenience. In many practical situations this simplified approach does not describe the dynamics of the structure with sufficient accuracy because of the complicated damping mechanisms that occur in practice. Theoretically speaking, any model that makes the energy dissipation function non-negative is a possible candidate for a valid damping model. Research into the dynamics of structures with viscoelastic materials has concentrated on the time dependence using fractional derivative, GHM and other models. This paper considers the effect of nonlocal damping on the response of a structure. In a nonlocal model, the reaction force at any point is obtained as a weighted average of state variables over a spatial domain via convolution integrals with spatial kernel functions that depend on a distance measure. In physical terms the nonlocal damping or elasticity property often arises when two dimensional structures are modelled as one dimensional.

In this paper, a nonlocal viscoelastic foundation model is used to analyse the dynamics of beams and plates with a variety of boundary conditions. The model yields an integro-differential equation, and obtaining closed form solutions is only possible for a limited range of boundary conditions by the transfer function method. This paper will present approximate solutions using the Galerkin method for beams and plates with typical spatial kernel functions. This requires the approximation of the displacement to be defined over the whole domain. To treat more complicated problems with variable damping parameters, non-uniform section properties, intermediate supports or arbitrary boundary conditions, a finite element method for beams is developed. However, in nonlocal damping models, nodes remote from the element do have an effect on the energy expressions, and hence the damping matrix is no longer block diagonal. The expressions for these direct and cross damping matrices are obtained explicitly for several common spatial kernel functions. The approach is demonstrated on a range of examples. The form of the nonlocal foundation model is shown to have a significant impact on the dynamic characteristics of structures.

6169-32, Session 5

A new model characteristics predicting approach for sandwich plate by using finite element method

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this paper presents a special and new approach to predict the dynamic behavior of a sandwich plate. in this study, simplified formulation of three layers viscoelastically sandwiched plate is adopted, complex mass and stiffeness matrices are proposed, calculated and handled to extract the eigenfrequencies, shape modes and their respectif modal damping loss factors. simple finite element is used. the utility of this strategy is to treat the complexe structure, the sandwich one without need of special sandwich finite element. it means that any commerialised finite element package will be upgraded by adopting this strategy to treat such complex structures. comparisons between calculated and experimental results show the success and effeciency of the presented approach.

6169-46, Poster Session

Vibration characteristics and dynamic behavior of multiple story buildings allowed to uplift

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It has pointed out that uplifting response can reduce seismic force of buildings. In this paper, to understand this phenomenon from the point of view of modal analysis, vibration characteristics and dynamic behavior of multiple storey buildings allowed to uplift are investigated by numerical analysis.

Analytical models are simplified 2-dimensional multiple storey buildings with vertical springs at the bottom, where uplifting is allowed. Models are assumed to be elastic. Structural parameters are the ratio of height to width of building, the stiffness ratio of building to springs and natural period of fixed-base model.

At first, eigenvalue analysis is carried out to clarify the vibration characteristics such as natural period, eigenvector, and effective mass. The results are compared with those of fixed-base models.

Next, dynamic behavior is investigated to clarify the effects of higher modes on responses, distribution of shear force along the height and the amount of energy which can be stored as potential energy of self-weight. Dynamic behavior is initiated by means of just adding a certain level of initial horizontal velocities to the model at rest. The distribution of initial velocities along the height is proportional to the 1st mode shape of fixed-based model. Direct integration method is used after initiating dynamic behavior.

The results of eigenvalue analysis of uplifting models are summarized as follows:

(a-1) The natural period of 1st mode becomes longer as the spring stiffness decreases. On the other hand, natural periods of higher modes are not so affected by stiffness of spring and those ranges are approximately equal with those of fixed-based model.

(a-2) The 1st mode shape becomes approximately linear as the spring stiffness decreases. So, participation vector of inter-storey shear deformation of higher modes can be larger than that of 1st mode.

(a-3) Effective masses of uplifting model against horizontal ground motion are approximately equal to those of fixed-based model.

The results of dynamic analysis are summarized as follows:

(b-1) Horizontal and uplift displacements are dominated mainly by 1st mode, which is similar to rigid body motion.

(b-2) Higher modes have much effect on the storey shear force responses. This corresponds (a-2) mentioned above.

(b-3) Storey shear force is smaller than that of fixed-based model up to middle part of buildings. But it can be increased in the upper part.

(b-4) More than half of total energy can be temporally stored as potential energy of self-weight.

6169-47, Poster Session

Seismic response reduction of buildings by rocking structural systems with adaptive dampers

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We are now developing rocking structural systems to reduce seismic responses of buildings. While a building is uplifting due to rocking against a strong earthquake, a part of seismic input energy is temporally stored as the potential energy of the self weight. Then the stress energy of the building, which causes directly structural damages, is reduced. The rocking structural systems are based on this principle. On the other hand, the uplift response may bring destructive impulse forces to vertical structural elements and amplify the roof displacement excessively. Thus we need generally install some damping devices at column bases on the grand floor or under footing beams to control the uplift response when applying the rocking structural system to a building.

In this paper, adaptive dampers are used as the damping devices of the rocking structural systems. Using adaptive dampers, we can change damping coefficient of damping devices according to a sign of vertical velocity at each uplifting part. When a building starts uplifting, and when the sign of vertical velocity is plus, we should set moderate damping coefficient to the damping devices so that they do not restrain a building from uplifting. When the building is landing, and when the sign of the vertical velocity is minus, we can set larger damping coefficient to them so that they can dissipate seismic energy and reduce the uplift and roof displacements as much as possible. To change the damping coefficient, we do not need a sophisticated vibration control rule. Principally we need only notice the sign of vertical velocity and need the simple “on-off control rule”. We can realize this on-off control rule only by introducing some mechanisms to each viscous damper.

To verify seismic performance of the proposed system with the adaptive dampers, numerical tests are carried out. A building structure is replaced to a one-mass system with a footing beam. The height and the width are 30 m and 8 m respectively. The first natural period is 1.0 sec. The 1940 El-Centro NS and the 1995 Kobe NS are input for seismic response analyses. The seismic responses of the proposed system are compared with those of a fixed-base system, a simple rocking system without any damping devices and a rocking system with conventional viscous dampers of which damping coefficient is always fixed.

The results of numerical tests are summarized as the following;

1) The maximum base shear of the simple rocking system became smaller than that of the fixed-base model. However, the roof displacement of the simple rocking system was amplified excessively.

2) The rocking system with the conventional viscous dampers could reduce both the base shear and the roof displacement. However, this system could not reduce the base shear when too large damping coefficient was set to each damper to reduce the roof displacement more.

3) The rocking system with the adaptive dampers could reduce both the base shear and the roof displacement more than other rocking systems.

From these results, it is concluded the proposed rocking system with adaptive dampers can effectively reduce seismic responses of buildings.

6169-48, Poster Session

Analytical methodology of magneto-rheogical fluid damper based on annular mixed modes employing eyring constitutive relationship

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Due to its mechanical simplicity, high dynamic range, low power requirements and robustness, Magnetorheological (MR) fluid damper can mesh well with application demands and constraints to offer an attractive means of protecting civil infrastructure systems against severe earthquake and wind loading and of improving monarchical system behavior against vibration. So far, Bingham plastic constitutive model has been widely used to in the evaluation and depiction of MR fluid rheological behaviors. Even though the Bingham plastic constitutive model is mathematically simple [2, 3], it has exhibited discontinuous characteristics in the shear stress versus shear rate, which have deficiencies in the representation of MR fluids pre-yield behaviors and post-yield behaviors and cannot accurately account for practical behaviors. In this paper, according to experiment data from laboratory, the Eyring constitutive model parameters have been identified via optimization of the error function of shear stress depicted by experimental test and the Eyring constitutive. Authors have theoretically set up flow equations for MR fluids in annular channel using the Eyring constitutive model and obtained velocity profile of MR fluids though annular channel. In accordance with piston velocity and annular channel geometrical parameters of MR damper, MR damper performances have been predicated by means of analysis methodology developed in this paper in order to determine design parameters. In the light of technical requirements for front suspension of Changan star minibus, a Magneto-rheogical fluid damper, which is designed and fabricated according to design method presented in this paper, has tested by electro-hydraulic servo vibrator and it’s control system in National Center for Test and Supervision of Coach Quality. The experimental results reveal that the analysis methodology and design theory are reasonable.

6169-49, Poster Session

Evaluation of power output for energy scavengers based on environmental sound energy

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The system that harvests from their environments are of considerable interests for use in self powered devices. In the generality of cases, these energy harvesting systems are used in the piezoelectric materials as mechanisms to convert mechanical vibration energy into electric energy. However, it is hard to find other energy instead of vibration energy source. Therefore, energy harvesting using the environmental sound energy is proposed instead of vibration energy. For very low powered devices, environmental sound energy may be enough to use power source. Environmental sound, e.g. insect is recorded and used as acoustic exciting source at acoustic tunnel. PVDF attached in acoustic tunnel make an electric energy by acoustic exciting. Here, environmental excited sound is modeled as a monopole source and calculated radiation power. We evaluate the electric charge output. We also discuss the developing system of the piezoelectric energy scavenger. An experimental verification of the model is also performed to ensure its accuracy.

6169-33, Session 6

Nonlinear dynamics of a SMA passive vibration isolation device

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Shape Memory Alloys (SMAs) have attracted much attention as potential materials for the use in passive vibration isolation systems, especially in the aerospace industry. Pseudoelastic SMAs are very attractive for passive vibration control, due to their ability to sustain and retrieve large amounts of strains, dissipate high levels of energy and provide a restoring force to the system. Energy dissipation is an intrinsic characteristic of SMAs and is related to the martensitic phase transformation and hysteresis. The amount energy dissipated is proportional to the degree of phase transformation achieved during a loading/unloading cycle for either complete or partial phase transformation.

SMA passive vibration isolation devices can be effectively used to attenuate vibrations transmitted to precision instruments in satellites, during on-orbit operations and launch, where high loads can be developed. They can introduce variable stiffness and provide additional energy dissipation, as a consequence of stress-induced martensitic phase transformation and hysteresis. Variable stiffness may shift the natural frequency away from the resonance, while energy dissipation largely reduces the transmissibility at resonance, where large deformations and displacements occur.

This paper investigates the nonlinear vibration of a passive damping vibration device, where the main elements are pseudoelastic SMA wires. The main focus of this work is placed on the numerical simulations. At first, a one-degree of freedom SMA oscillator, composed of a mass balanced by two pseudoelastic SMA wires, was considered. A thermodynamic constitutive model capable of predicting SMA responses, including minor hysteresis loops (partial martensitic phase transformation) and temperature variations due to phase transformation was used. Transmissibility curves, phase plots, Poincaré maps and bifurcations diagrams were used to investigate how the motion of the oscillator was affected by the SMA intrinsic nonlinearities. Afterwards, the numerical results were compared with experimental results of a previous work, where the transmissibility curves and temperature variations were obtained from sine sweeps vibration tests.

The intrinsic energy dissipation characteristic of SMAs is a very complex phenomenon, and can be a function of several factors, such as loading history, temperature, frequency, etc. Therefore, a constitutive model that is able to accurately simulate the pseudoelastic SMA response was needed. For this reason, the thermomechanical constitutive model for SMA proposed by Qidwai and Lagoudas

was implemented. Even though, the model is able to predict the main characteristics of the SMAs pseudoelastic response, it was modified to consider some other necessary features. At first, the hardening function, which is responsible for the transformation-induced strain hardening, was changed to account for smooth transitions between the elastic and phase transformation regimes. This modification eliminated the presence of sharp corners in the stress-strain curve at the beginning and at the end of the martensitic phase transformation. Therefore, the response of a polycrystalline SMA wire could be better represented, where grains with different orientations start and finish the phase transformation at different times. Afterwards, the model was improved to predict the temperature variation of the SMA wire due to martensitic phase transformation and heat exchange with the environment during the vibration tests.

The next modification conducted on the model was regarded to the prediction of minor loops. It is not guaranteed that the SMA wires will always undergo a complete phase transformation, following the major loop of hysteresis path in a vibration test. For this reason, it was necessary to extend the model so that it could predict minor hysteresis loops properly. The procedure of computing the evolution of internal state variables during minor loops was based on the work by Bo and Lagoudas. In this way, the model gained the capability of accounting for the effects of changing loading paths induced by cyclic loading, even when such minor loops are close to the transformation start and finish points. The paper also discusses the numerical implementation of the constitutive model. A similar procedure described in Qidwai and Lagoudas was followed.

Now that the nonlinear constitutive behavior of the SMAs has already been defined, the integration of the equations of motion of the oscillator was the next task. Since the SMA response is highly nonlinear, an efficient and reliable numerical method should be employed to assure stability and convergence of the solution. For this reason, the Newmark integration scheme was used to compute the time response of the system. It is also important to mention that, due to the intrinsic nonlinearities presented by SMAs, the dynamics of the oscillator can present a very rich class of solutions, evolving from periodicity to chaos. Therefore, Poincaré maps, bifurcation diagrams, and phase plots, as well as transmissibility curves were used to analyze the dynamics of the SMA oscillator.

The paper finalizes its discussion comparing numerical results with experimental results from a previous work. The experiment consisted of exciting a SMA passive vibration isolation device with a series of continuous sinusoidal acceleration functions in the form of a sine sweep. The SMA vibration device was composed of a frame, two low-friction ball bearings, a mass, and two pseudoelastic SMA wires of equal length, connecting the mass to the frame (both top and bottom). Each SMA wire was preloaded with sufficient preload to assure that the wires remain in tension throughout the test. Frequency responses and transmissibility of the device were analyzed for the case where the SMA wires were pre-strained at 3% and 4% of their original length. The temperature of the wires was recorded during the dynamical tests, where a large variation was observed.

In summary, this paper discusses the nonlinear vibration of a SMA passive vibration isolation device. A constitutive model for SMAs was modified to predict minor hysteresis loops and temperature variations. The dynamics of a SMA oscillator was numerically investigated, where a rich class of solutions was observed. Numerical results were compared to the experimental results of dynamical tests.

6169-34, Session 6

In-situ model identification and its applications to optimization of vibration isolation systems

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Vibration isolation systems play crucial roles in many industries including automotive and aerospace. In vehicles for example, engine mounts protect the engine from excessive movement and forces due to low frequency road and high frequency engine excitations. Or, body mounts protect the cabin from vibration forces exerted by the body. Normally, vibration isolation devices are conceived at early stages of design knowing the model of the system and subsequently, they are tuned in the refinement stage to improve the system's noise, vibration, and harshness (NVH) response. This approach in complex systems fails because of the lack of a comprehensive model or large errors or assumptions made during the design phase. In a vehicle for example, the noise path from the road and hence, from the wheels to the engine consists of many subsystems and interconnection that the model prediction usually is way far from the actual response in the refinement phase. As a result, the refinement phase becomes the actual design phase.

Currently, noise path analysis (NPA) is used for the design of vibration isolation systems. Although, this method is an in-situ approach however; it is based mostly on trial and error and very time consuming. Furthermore, it does not lead to an optimum vibration isolation system for a given objective function. In theory, it is possible to arrive at more accurate models experimentally at the refinement phase. This requires disassembling the system into its subsystems and performing experiments to identify the models. Although this sounds simple, it is not favourable to NVH companies due to the complexities involved and also the differences in the identified model and actual assembled system because of the effects of preloads on the subsystems dynamics.

In this paper, an in-situ method is introduced to find the optimum set of vibration isolation devices for a given system. In the new technique, the system does not need to be disassembled and FRF-based substructuring (FBS) synthesis and standard NVH testing are used to obtain frequency response function (FRF) models of the subsystems and hence the overall system model. The model is linked to an optimisation routine to predict the optimum set of vibration isolation devices for a desired objective function.

For evaluation and verification, this approach has been applied to the optimization of body mounts (vibration isolation devices between the chassis and passenger cab) of a pick-up truck. The focus of the optimization is on the role of the body mounts in attenuating structure-borne noise and vibration from chassis to the cab. A numerical optimization problem is formulated to find the best set of body mounts resulting in the lowest level of vibration of a selected objective point in the cab for a given road induced excitation applied to the four wheels. Experimental results are presented to show the effectiveness of the in-situ approach in finding the optimum body mount set.

6169-35, Session 6

Fuzzy skyhook control of semiactive suspensions using self-organizing controller

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Skyhook control method has been used widely in vibration control of semi-active and/or active suspension systems since it was proposed by Karnopp in 1974. A lot of research results have been reported its outstanding performances in literature. Recently, some researchers including Yanming Liu showed that the performance of skyhook control could be improved more when fuzzy logic is incorporated suitably. However, the most difficult problem in using fuzzy logic for control purpose is to select suitable linguistic control rules of the fuzzy controller.

In most of cases, the linguistic control rules are obtained from the designer's experiences and tedious trial and error tuning. It may be the same case for ER (Electro-rheological) damper in semi-active suspension system.

The SOC(Self-organizing controller) was proposed by Procyk and Mamdani in 1979 to obtain suitable fuzzy control rules automatically. It has not been used so widely in the field of fuzzy control. However, several interesting applications have been reported year after year. We have developed a fuzzy skyhook controller for ER semi-active suspension system using SOC in order to apply to a commercial vehicle produced by KIA motors in Korea.

2 DOF (Degree Of Freedom) quarter car model of semi-active suspension is used for simulation. The parameters of the quarter car model were obtained from measurements and experiments for that vehicle. Road condition, which is used as an input for simulation, is expressed as a function of road roughness coefficient, wheel speed and white noise.

In this paper, the fuzzy skyhook controller consists of a skyhook controller module for damping force generation, FLC (Fuzzy Logic Controller) for damping force coefficient adaptation and control rule acquisition algorithm for the modification of control rules through performance evaluation. Speed of sprung mass and unsprung mass are used as input linguistic variables of FLC and are expressed as 7 triangular membership functions. The damping coefficient which determines damping force is used as an output of FLC and COG (Center Of Gravity) is used as a defuzzification method.

The performance evaluation method for FLC is implemented as continuous type FLC evaluator for this application even though quantized type performance index table has been used widely in the literature. The control rules are adjusted to decrease the acceleration of sprung mass to improve the comfort of passengers by using the rate of acceleration of the sprung mass as an input of the fuzzy logic.

In order to verify the performance of the proposed fuzzy skyhook controller with SOC, numerical simulations about random road input which express rough road surface and bump road surface which express sudden impact input of road surface are performed. From the simulation results about random road input, we can confirm that the fuzzy skyhook controller which is tuned by the proposed SOC algorithm is operated as good nonlinear controller and outperforms the ordinary well-tuned skyhook controller. Simulations for bump road condition use 3 inch bump. The vehicle passes the bump with the speed of 10km/h and 40km/h. Simulation results show that the proposed fuzzy skyhook controller outperforms about 35% the ordinary skyhook controller.

Even though the improvement of control performance is decreased due to increment of the vehicle speed, it is verified that the proposed fuzzy sky-hook controller outperforms the well-tuned ordinary sky-hook controller.

6169-37, Session 7

Analysis of damping characteristics of a viscoelastic polymer filled with randomly oriented single-walled nanotube ropes

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Carbon nanotube (CNT) based materials, such as densely packed CNT thin films (Koratkar et al., 2002a, b, 2003; Lass et al., 2002, 2003) and polymeric composites with dispersed CNT fillers (Wang et al.,2004; Zhou et al., 2004a, b, c; Suhr et al., 2005; Liu et al., 2005a, b), have recently attracted a lot of interest because of their unique damping properties. Due to their large surface area, large aspect ratio, high stiffness, low density, and high thermal conductivity, CNTs could be ideal fillers for high performance damping composites.

Based on the "stick-slip" phenomenon previously observed at the atomic scale on graphite surfaces (Buldum and Lu, 1999; Hölscher et al., 1998), structural damping models of CNT-based composites have been developed by applying this "stick-slip" motion to the nanotube/resin interface as well as the nanotube/nanotube interface (Zhou et al., 2004a, b, c; Liu et al., 2005a, b). Zhou et al. (2004a, b, c) developed a "stick-slip" damping model for composites containing well-dispersed individual SWNTs and aligned nanoropes and performed damping measurements on CNT-based composites. Analytical and theoretical results showed a strain-dependent damping enhancement due to "stick-slip" motion at the interface of the SWNTs and the resin as well as the interface of the nanotubes in the ropes.

The damping properties of polymeric composites with well dispersed, randomly oriented, CNT ropes were investigated by Liu et al (2005a, b) using the "stick-slip" concept. The composite was modeled as a three-phase system composed of a resin, a resin sheath acting as a shear transfer zone, and SWNT ropes. To show the inter-tube sliding effects due to nanotube aggregation, the Young's moduli and loss factors of composites filled with aligned SWNTs, aligned nanoropes, and randomly oriented nanoropes were compared. The analytical results indicated that significant improvement of Young's modulus could be achieved by fully dispersing well aligned SWNTs in the polymeric materials. Similarly, fully dispersed, well-aligned SWNTs provided the greatest loss factor and energy dissipation capability of all the cases considered when the applied stress was high enough to cause complete sliding of all the SWNTs or nanorope fillers.

While the recent study presented by Liu et al. (2005a, b) is a necessary step toward modeling the damping characteristics of nanorope-filled-composites, it is still limited by only focusing on the damping effects due to interfacial friction between nanorope fillers and polymeric materials under uniaxial loading. Since polymeric matrix materials possess viscoelastic properties that will be influenced by the nanotube fillers and at the same time affect the overall damping, their characteristics need to be included in the model and analyzed. The objective of the research presented in the current paper is to address this issue and advance the state of art in damping characterization of nanorope filled composites.

Based on the viscoelastic material theory (Shames and Cozzarelli, 1991), the CNT-based composite is modeled as a three-element nonlinear viscoelastic model (NVM). A linear spring and a Newtonian dashpot in series are utilized to constitute the standard linear Maxwell model (Shames and Cozzarelli, 1991). The nonlinear response due to the "stick-slip" movement between nanotube/sheath interfaces is associated with a Coulomb friction element connected in parallel with the Maxwell model. A harmonic loading is applied to the composite. The effective loss factor is defined as the ratio of the dissipated energy per unit volume and the maximum stored energy per unit volume (Lazan, 1968), where the dissipated energy includes both the energy dissipated in viscoelastic polymeric materials and the energy dissipated due to the interfacial friction between nanotube/rope and sheath. Utilizing this new model, extensive parametric studies are performed. It is illustrated that the "stick-slip" friction is the main contribution for the total loss factor of the CNT-based composites even with small amount of nanotubes/ropes. The loss factor due to viscoelatic polymer decreases as the frequency of the applied loading increases while the loss factor due to "stick-slip" friction is frequency independent. From the analysis, it is shown that there is an optimal loading magnitude to achieve maximum effective loss factor.

6169-38, Session 7

Effect of nanotube-matrix covalent bonding on the stiffness and damping properties of polymer nano-composites

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Surface modification of singlewalled carbon nanotubes (SWNT) are first conducted using an epoxidation process and then the nanotubes fillers are uniformly dispersed in a polycarbonate (PC) matrix in order to investigate the effect of establishing covalent bonds (linkages) at the interfaces between nanotube fillers and polymer matrix. Epoxidized SWNT-PC and as-received SWNT-PC nanocomposites as well as baseline (pristine) polycarbonate samples are dynamically tested using an MTS-858 servo-hydraulic test facility. The tests are performed over a wide range of strain amplitudes and frequencies. The results indicates that the epoxidized SWNT-PC composite shows significant reinforcement in the elastic moduli, compared to as-received SWNT-PC composite, which only have van der waals (non-bonding) type interactions, indicating that a covalent bond forms between the surface modified (or epoxidized) nanotubes and polymer chains. For the as-received SWNT-PC composite the storage modulus decreases and loss modulus increases significantly as the strain amplitude is increased, which is indicative of tube-matrix interfacial slip. In contrast, the epoxidized SWNT-PC samples show relatively strain-independent storage and loss moduli over the entire strain range. This indicates that stronger interfacial strength (as a result of covalent boning) can inhibit filler-matrix sliding thereby lowering the damping response and enhancing the stiffness.

The results shown in this paper indicate that surface modification of carbon nanotubes can be used to establish covalent linkages between the nanotube fillers and the matrix materials. These covalent linkages are effective at preventing interfacial slip resulting in enhanced stiffness coupled with reduced structural damping

6169-39, Session 7

Next generation advanced nanoparticle-based damping solutions for aerospace components

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It is now accepted that nanotechnology can help solve vibration damping and high noise issues through the utilisation of nanomaterials (or media) that dissipate a substantial fraction of the vibration energy that they receive. Damping materials are often used in conjunction with ceramics or fibre-composites to yield structures with enhanced vibration performance. While significant advances have been made in the field of active damping systems in recent years, interesting and important developments have also occurred with passive damping elements in systems.

Across a wide range of industries, our new found understanding of the nanoscale damping phenomenon is enabling existing damping technologies to become economically feasible, and offering new solutions to existing vibration damping (dynamic) problems. Recent years have seen great advances in carbon nanotube development and active surfaces with applicability to composite materials strengthening and armoring [1-4]; however, the main issue is the need to match applications to technologies/materials being developed. Wide-ranging application of damping materials in real-life products is one of the best ways to ensure future development. Commercial utilisation of a damping technology depends from both technical performance and business environment for that. There must be a business support for extensive technology implementation during its life-cycle cost. This has often been seen to be a limiting factor in the utilisation of novel material/technology. In this situation, a broader understanding of the material and its potential application is of great benefit since a "secondary" feature can make the damping system more attractive than its predecessor.

Our international team has recently recognized a role of nanotechnology in vibration damping and discovered that enhanced vibration damping can be provided via nano-scale reinforcements where at least one dimension limited to between 1 - 100 nanometres and carbon nanotubes (CNT) are particularly the strongest and most flexible molecular cost-decreasing materials because of C-C covalent bonding and seamless hexagonal network architecture [3, 4].

The technology idea presented here is the advanced nanotechnology-based damping solutions for the next generation aerospace engineering that provides normal materials with unique benefits. The technology at the core of the concept is a nanoparticles/fibres/tubes-reinforced composite material and coating technology with regard to extensive dynamic characterization and modelling that includes two key elements: computational simulation and engineering workbench virtual design environment. The manufacturing design comprises several steps for tailoring the nanoparticle-matrix interface including control over parameters of tem-

perature, amplitude and frequency. The nanotechnology-based damping solution uses an advanced proprietary particle technology that manipulates the structure of the material at the nanoscale level through its saturation with carbon nanotubes. The nanoparticle-reinforced material is free from health-damaging sensitivity to temperature and loading, which are enhanced by strong C-C covalent bonding and seamless hexagonal network architecture. Thus carbon nanotube plays the role of a damping spring, capable of increasing the dissipation energy in the material by a factor of thousands.

The novel concept of nanoparticle-based damping technology shows that a molecule-level mechanism can considerably enhance vibration damping and dynamic of aerospace components (fan blades) via enhanced energy dissipation because of large surface-to-volume aspects in nanoparticle-reinforced composite material, large damping energy sources for friction and slip-stick motion at interfaces of matrix and nanoparticle. Thus carbon nanotube can act as a simple nanoscale damping spring in aerospace materials and is suggested for aerospace damping materials of the next generation. The materials offer the potential to further reduce the mass and dimension, increase performance, and reduce vibrations.

As a result the nanoparticle/tube/fibre-reinforced composite material gains advanced damping properties compared with conventional materials reinforced through available technologies as well as other types of commercialized damping solutions. The damping properties of the material can be further enhanced by designing unique aerospace components based on personal manufacturer needs of either civil or military aircrafts. Personalized set of nanoparticles can be introduced into material matrix, for example, through the CVD-based technology combined with conventional particle technologies (thermal spraying, PVD, etc.).

The principal conclusions are that by invoking the properties of nano-auxetics/nanostructures it is possible to control the wave/sound/vibration propagation in the material and enhance the energy dissipation that can assist in improving the inherent damping of materials, but an experimental/theoretical environment is required to apply it. Nanoparticles/tubes can be used as a reinforcement of a matrix to provide multi-functionality, and thus we need to create an environment (knowledge) to introduce nanomaterials widely in industry. In this respect developed computational tools and engineering workbench is important part of next generation aerospace design.

6169-41, Session 8

Semiactive TMD with piezoelectric friction dampers in floor vibration control

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Abstract: Floor systems with thinner slabs and lighter materials are more prone to excessive vibration caused by repetitive human activities such as walking. When considering resonant vibrations, increasing the damping in the floor can have a dramatic effect on what is often a very lightly damped system. Passive tuned mass dampers (TMDs) and active mass dampers are commonly proposed for this purpose. However, since passive TMDs often require a large mass for adequate effectiveness, their use is often prohibited because of overload on existing structures. On the other hand, the initial cost of active mass dampers is prohibitive because the precision electric motor is too expensive.

A semi-active variable damping TMD (SAVDTMD) seems to be a good combination of passive TMD and active mass damper. In this type of device, the passive fixed dampers of the TMD are substituted by the actively controlled dampers. The benefit of actively controlled dampers is that the weight of the moving mass can be reduced without loosing the effectiveness of the heavier passive TMD. While the damper in a passive TMD exerts a force that reduces the relative velocity between the annoying floor and TMD mass, it does not always reduce the absolute velocity of the floor. An active damper can be configured to target absolute floor velocity instead of relative velocity, thus increasing effectiveness without requiring a lot of control force.

Using a SAVDTMD for floor vibration control has been investigated by others using an equivalent SDOF floor model with a semi-active hydraulic fluid damper. While this method shows promise, these studies do not include the effects of the untargeted floor modes or servo-valves, which may cause a backlash effect in the generation of control forces. In this paper, a study which analyzes the application of SAVDTMD with a piezoelectric friction damper to MDOF floor models is presented. Since piezoelectric friction dampers do not have servo-valves, the need to include the backlash effect is eliminated. The use of a MDOF floor model in the analysis provides some insight on the effect of modes not targeted in the design of the controller. An optimal semi-active control law originally developed for vehicle suspension control was incorporated into the analytical models. Two floor system examples, typical of those that would have a floor vibration problem, are evaluated and shown to be controlled successfully by the SAVDTMD at both the targeted and untargeted modes. Problems of spillover of the control force to untargeted modes was analyzed and determined to be stabilizing.

6169-43, Session 8

Transient characteristics of an MRE-based vibration absorber

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The transient performance of a state-switched absorber (SSA) employing magnetorheological elastomers (MREs) as tunable springs was examined. State-switched absorbers (SSAs) consisting of masses, dampers, and changeable springs, have been found to reduce energy and base displacement in vibration applications with multiple frequency excitations. However, an SSA must be able to change its natural frequency in less than a quarter-cycle of the frequency of interest to avoid risks of instability. The SSAs discussed in this work were subjected to step changes in magnetic fields, and the time-dependent frequency response was evaluated.

The SSA used in this work consisted of a low-carbon steel and magnet wire coil mass, and four MRE pieces that behaved as complex springs. The wire coil was used to generate a magnetic field within the absorber. The MREs were subjected to the absorber's magnetic field in a path of least resistance. The design was generated in part using finite element simulating software.

MREs were used as springs because an MRE's stiffness increases in the presence of a magnetic field. MREs were manufactured using a two-part silicone gel with a Young's modulus of approximately 25 kPa and low-carbon iron micro powder, 6-9 microns in diameter. MREs were created to contain specified volume fractions of iron powder, and then placed in a magnetic field during the curing process. This generated MREs with iron particles aligned in chains, which amplifies the stiffness increase effect.

MREs were placed in vibration absorber configurations such that the magnetic field applied to the MREs was parallel to the direction of vibratory excitation. The SSA was attached to a base mass which was subjected to band limited white noise excitation, which was also measured with an accelerometer. A displacement probe attached to the base mass was used to measure the displacement of the absorber mass relative to the base mass.

This work comprised of two primary experiments: determining the natural frequency of the SSA at a set level of excitation amplitude, magnetic field, and iron content, and determining the transient nature of the natural frequency when a step change in magnetic field was generated, or how the natural frequency changed over time. The SSA's natural frequency was determined as it varied with MRE iron content, excitation amplitude, and magnetic field intensity levels. FFTs of the displacement data were taken and fit to a linear, ODE model using a method of least squares.

6169-44, Session 8

Mitigation of acoustic resonance using electrically shunted loudspeakers

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Low-frequency reverberant sound fields are usually suppressed by means of either adaptive feedforward control or Helmholtz resonator. Feedforward systems utilize a noise reference signal, error microphone, and loudspeaker to cancel sound propagating in one direction. Due to the requirement for multiple transducers and a powerful Digital Signal Processor, feedforward systems are the most complex and expensive option for acoustic noise reduction. Helmholtz resonators, comprising of auxiliary coupled acoustic chambers, are a popular passive technique for the control of dominant acoustic modes. Although lightly damped acoustic modes can be heavily attenuated, the resonators are difficult to tune and require impractically large cavity volumes at frequencies below 200 Hz. This paper introduces a new technique for the control of low-frequency reverberant sound fields.

By connecting an electrical impedance to the terminals of an acoustic loudspeaker, the mechanical dynamics, and hence acoustic response can be made to emulate a sealed acoustic resonator. No microphone or velocity measurement is required. In some cases, the required electrical circuit is simply the parallel connection of a capacitor and resistor. With the addition of a single pressure microphone, a technique for online circuit adaptation is proposed. Experimental application to a closed acoustic duct results in 14 dB pressure attenuation of a single acoustic mode. Active impedances can be designed by viewing the system model from a feedback control perspective. The resulting electrical impedances, although not passive, are experimentally shown to attenuate four acoustic modes by up to 10 dB.

6169-45, Session 8

Electrostatic tuning of the bending stiffness of a large scale GFRP-CFRP beam

A. E. Bergamini, R. Christen, M. Motavalli, EMPA (Switzerland)

The suppression of vibrations of a structure is commonly considered a necessary measure for the extension of its lifetime, when high amplitude vibrations are observed. As an alternative to the introduction of discrete damping devices, the modification of the stiffness of a beam is proposed as a means to suppress vibrations due to resonance. The effect of electrostatic tuning on the vibratory properties of small beams has been demonstrated in previous work. New vibration suppression strategies are also of interest for large size structures, such as automobiles, airplanes and lightweight civil engineering structures that are prone to vibrations induced by the combined effect of wind and possibly rain. In order to confirm the practicability of such an approach also on larger structures, a large size (2400mmx60mmx120mm) GFRP I-beam of a type used for the construction of lightweight pedestrian bridges has been equipped with stiffening elements that can be coupled electrostatically. The dynamic behaviour of such a cantilever beam was investigated as a function of excitation amplitude and frequency. The expected increase in stiffness for an optimally bonded system is of the order of three and a half times, which would yield a shift of the natural frequency of the order of 100%. The results show that in a sub-optimal system, the first bending natural frequency of the beam can be shifted by approximately 30% by electrostatically coupling CFRP strips to the surfaces of the GFRP beam. Additionally, the hypothesis that the interaction between the stiffening elements and the core of the system are governed by a stick-slip type behavior could be confirmed by performing measurements with low amplitude excitation. The behaviour of the system is nonlinear in terms of its dependency on the excitation amplitude. Other than in the case of high amplitude excitation, where friction at the core face interfaces plays a dominant role in the reduction of the vibration amplitude, as confirmed by a marked broadening of the peaks in the transfer function, fairly formed resonance peaks could be observed in low amplitude experiments. The results indicate that further work is needed towards the optimization of the interfaces between faces and core of the sandwich beam and towards the properties of the dielectric materials used. Such work will make it possible to reduce interfacial slipping also at higher excitation amplitudes, thus leading to reduced wear of the contact surfaces and increased reliability of the system.

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6170-01, Session 1

A non-equilibrium thermodynamics framework for domain evolution; phase field models and finite element implementation

C. M. Landis, Rice Univ.

Traditionally, the Ginzburg-Landau equation governing the evolution of domain configurations has been derived from a simple and physically justifiable set of assumptions. While this approach is certainly sound, it obscures the modern continuum physics distinction between fundamental balance laws, which are applicable to a wide range of materials, and the constitutive equations that are valid for a specific material. Here we present a small deformation non-equilibrium thermodynamics framework for ferroelectric domain evolution. In addition to the macro mechanical (static equilibrium) and electrical (Maxwell's laws) balance laws, we also postulate a configurational force balance governing a set of configurational forces (also called microforces) that are work conjugate to the order parameter, which in our case is the material polarization. Application of the second law of thermodynamics to this system allows us to identify general forms for the free energy and the dissipation coefficient of the material. The general form of the theory contains the standard Ginzburg-Landau equation as a special case. In order to make computations on relevant size scales with these types of phase field models, it is important to apply adaptive grid techniques with fine meshes near domain walls and coarse meshes elsewhere. Such adaptive meshing techniques are currently available for finite element methods. Hence, as a step towards large-scale phase field computations, a finite element method for the solution of these types of phase field theories is described and implemented. Preliminary results from the model and its finite element implementation on ferroelectric thin film domain evolution will be given.

6170-02, Session 1

Coupled modeling and simulation of electro-elastic materials at large strains

G. Possart, P. Steinmann, Univ. Kaiserslautern (Germany)

In the recent years various novel materials have been developed that respond to the application of electrical loading by large strains. An expample is the class of so-called electro-active polymers. Certainly these materials are technologically very interesting, e.g. for the design of actuators in mechatronics or in the area of artificial soft tissue biomechanics.

This presentation focuses on the modelling of these materials within the setting of continuum-electro-dynamics specialized to the case of electro-elasto-statics and the corresponding computational setting. Thereby a highly nonlinear coupled problem for the deformation and the electric potential has to be solved.

As an interesting and probably less known aspect the presentation highlights also the theoretical and computational treatment of various defects, like e.g. cracks or inclusions, for this example of a coupled multiphysics problem. The discretization of the fully material setting of the relevant balance equations renders immediately nodal configurational forces with all the intriguing information richness they provide. The study of configurational continuum physics renders a valuable tool for the analyst in order to examine further properties of the solution which would otherwise stay hidden.

6170-04, Session 1

Finite-element-analysis of poling processes in piezoceramic devices

M. Kamlah, B. Laskewitz, Z. Wang, Forschungszentrum Karlsruhe (Germany)

Recent advances in the formulation of a micromechanically motivated constitutive model will be presented. The model will be compared to experimental results.

Furthermore, the finite element implementation of constitutive models for piezoceramic materials will be discussed.

Finally, we discuss examples for the application of such a tool to the analysis of poling processes in piezoceramic devices.

6170-05, Session 1

Monte Carlo simulation of ferroelectric relaxor crystals at morphotropic phase boundary

J. Li, Univ. of Nebraska/Lincoln; K. Bhattacharya, California Institute of Technology

In this talk, we report our recent work on ferroelectric relaxor crystals at morphotropic phase boundary (MPB) using a Monto Carlo simulation, where the evolution of a two-dimensional lattice of dipoles under an applied electric field is studied. Each lattice point is either tetragonal or rhombohedral, while each dipole can take any one of the eight available polarization directions with certain probability determined by the overall energetic state. As the dipoles evolve to an equilibrium configuration, microscopic clusters and macroscopic hysteresis loop have been observed, and the effects of chemical compositions and temperature have been investigated. In particular, we have confirmed the mesoscopic polarization rotation near the MPB, which is believed to be responsible for the superior electromechanical coupling observed in relaxor crystals near MPB.

6170-06, Session 2

Micromechanical modeling of PMN-32%PT ceramic based on single crystal properties

K. Webber, C. S. Lynch, Georgia Institute of Technology; R. Zuo, Technische Univ. Darmstadt (Germany)

The behavior of ferroelectric ceramic materials is governed by complex multiscale phenomena. At the macroscale, the constitutive behavior displays time dependent coupling between stress, electric field, and temperature. This behavior is dependent on composition, microstructure, and dopants. Plasticity based macroscale phenomenological models utilize the concept of internal state variables and their evolution to represent the volume average behavior. These models include many variables that must be determined through a combination of experiment and micromechanical modeling. At the mesoscale, the microstructure plays an important role in the material behavior. Grains form during the sintering process and porosity can occur at grain boundaries. Upon cooling, the material undergoes a phase transformation to a ferroelectric state. Domains form within grains to minimize intergranular stress and electric fields. Within a single domain, the material behavior is governed by the crystal structure and the local fields. Micromechanics approaches connect the mesoscale with the macroscale. Micromechanical models utilize single crystal behavior and a self consistent approach to handling intergranular stress and electric fields to simulate the macroscopic behavior. This approach considers average local fields and utilizes volume fractions of domain types to characterize the state. This work implements measured single crystal behavior in a micromechanics code to predict the macroscopic material behavior. Specimens of the same composition are characterized under combined stress and electric field loading and the results are discussed.

6170-07, Session 2

Phase field simulation of ferroelectric and antiferroelectric single crystals

T. Liu, C. S. Lynch, Georgia Institute of Technology

Ferroelectric materials exhibit spontaneous polarization, spontaneous strain and domain structures below the Curie temperature. The phase field approach has been used to simulate the ferroelectric-antiferroelectric phase transformation and the formation of ferroelectric domain structures. We simulate the evolution of phases and domain structures in ferroelectric single crystals by solving the time dependent Ginzburg-Landau (TDGL) equation with polarization as the order parameter. The TDGL model is based on thermodynamic theories and kinetics. In the TDGL equation the free energy of a ferroelectric crystal is written as a function of polarization and applied fields. Change of temperature as well as application of stress and electric field leads to evolution of polarization and change the free energy level. The temporal evolution of polarization field is computed by solving the TDGL equation with explicit time integration scheme. Finite difference method is implemented for the spatial description of the polarization. Different boundary conditions can are considered. This approach is capable of simulating structural phase transformations and domain evolution at nano- to micro-scales. Cubic to rhom-

bohedral and ferroelectric to antiferroelectric (rhombohedral) phase transformations are simulated. Formation of domain structures and preferred domain wall orientations are modeled. By applying temperature, stress and electric fields, field induced polarization switching and phase transitions can be simulated and the macroscopic material responses can be reproduced. Parameters are chosen according to measured energy levels to match the behavior of ferroelectric single crystals. This phase field approach provides a tool to simulate the evolution of domain structures based on microscopic parameters. It can be implemented in numerical codes as a material model to compute the field-microstructure-property relation and the macroscopic responses.

6170-08, Session 2

Micromechanics of multivariant and multiphase ferroelectric domain structures

J. Rödel, Dresden Univ. of Technology (Germany)

High-strain piezoelectric materials are often ceramics with a complicated constitution.

In particular, PZT is used with compositions near to a so-called morphotropic phase boundary, where not only different variants of the same phase (domains), but different phases may coexist.

Micro-mechanical models for ferroelectric ceramics would be much more realistic, if these effects could be incorporated.

In this presentation, we consider the conditions of mechanical and electrical compatibility of ferroelectric domain structures. One result are the well known crystallographic relationships between domains of the same phase for various phases. Furthermore we are able to address the question of coexistence of different crystallographic phases within the very same crystallite. In general, the spontaneous strain and spontaneous polarization of a tetragonal and a rhombohedral domain are not compatible. The internal fields which are caused by this incompatibility, and the associated energy contributions, can be calculated using distributed crystal defects and charge models.

We can also show that this internal fields and energies can be decreased by an intermediate, e.g. monoclinic, phase and we can calculate optimal, i.e. minimum energy interface orientations.

The numerical analysis of the derived relationships are susceptible to the crystallographic description of the phases in question. In this presentation, a simple analysis and analytical, composition dependent fit of strain and polarization of PZT at room temperature for available data are used.

The outlined approach can be used to model the overall behavior of multi-variant and multi-phase crystallites with certain, simplified geometrical arrangements of the constituents.

6170-09, Session 2

A real-space non-local phase-field model of ferroelectric domain patterns in complex geometries

K. Dayal, K. Bhattacharya, California Institute of Technology

Ferroelectric perovskites are used in various MEMS devices due to the strong coupling between electric field and strain. They also have large nonlinear responses to optical excitation for which they have been proposed as an element of photonics devices. In these applications, ferroelectrics are machined to have complex geometries with a complex arrangement of patterned electrodes. It is important therefore to understand the domain patterns that form in these complicated geometries. However, available phase field models assume periodicity or unrealistic electric boundary conditions to be useful in these contexts. Therefore, we develop a real-space non-local phase-field model to address this issue.

The key issue is to resolve not only in the dipole-dipole interactions in the ferroelectric but also stray or induced fields in the surroundings in a computationally effecient manner. We do so by using a boundary element method to account for the non-local electrostatic contributions, and this makes the modeling of free surfaces computationally tractable. The model is constructed by identifying the total energy consisting of Landau, domain wall and electrostatic contributions.

We calibrate the method by simulating AFM topography measurement experiments, and use this to test different hypotheses of closure domains at the free surfaces of ferroelectric crystals. We also simulate PFM experiments in an accurate and consistent manner, by modeling the charged tip and calculating the response to the PFM taking into account nonlinear effects, such as large fields near the tip, and local switching.

We also use the method developed to study the behavior of a ferroelectric crystal with patterned electrodes, a geometry that is of interest in the design of electronic devices with ferroelectrics. The ability of the boundary element method to handle free surfaces also allows us to study the nature of closure domains in ferroelectrics and the interplay between elastostatic energy and electrostatic energy. We also study configurations that are of interest in building photonics devices with barium titanate.

6170-10, Session 2

Multi-axial non-proportional polarization rotation tests of soft PZT piezoceramics under electric field loading

D. Zhou, M. Kamlah, B. Laskewitz, Forschungszentrum Karlsruhe (Germany)

In this experimental work, multi-axial, non-proportional polarization rotation tests were performed for a commercial soft PZT material under purely electric field loading. Large pre-poled piezoceramic plates were cut into rectangular blocks of 5 x 5 x 15 mm∏, with their long axes inclined at a set of angles (from 0° to 180°, in steps of 15°) to the initial poling direction. After cutting, the top and bottom 5 x 5 mm∑ surfaces were electroded with a thin layer of silver paint and, then a ramp-shaped electric field was applied to cause the polarization to rotate. In addition to the polarization measurement along the field loading direction, the normal strain responses in all three coordinate directions were monitored simultaneously using strain gauge technique. Based on a series of polarization and strain versus electric field curves, switching (domain reorientation threshold) surfaces were constructed in the bi-axial electric field space using the conventional offset method. The experimental data were used to examine the existing switching criteria in phenomenological and micromechanical models for the non-linear constitutive behavior of piezoceramics.

6170-15, Session 3

Temperature dependence of the dielectric, elastic and piezoelectric material constants of lead zirconate titanate (PZT) ceramics

G. Sabat, Dept. of National Defence (Canada); W. Ren, Xi'an Jiaotong Univ. (China); G. Yang, EXFO (Canada); B. K. Mukherjee, Dept. of National Defence (Canada)

Piezoelectric lead zirconate titanate (PZT) ceramics are widely used as sensors and actuators and some of the applications, such as those in space, involve environments in which the temperature varies over a wide range. It is therefore necessary to characterize the behaviour of these ceramics over a wide range of possible operating temperatures. We have used resonance methods to determine the variation of the material constants of PZT ceramics as a function of temperature over a temperature range from -165°C to 195°C.

Soft (EC-65) and hard (EC-69) PZT samples, manufactured by EDO Ceramic, were cut according to the prescribed aspect ratios and satisfying the following resonance modes: radial mode, thickness extensional mode, length extensional mode and length thickness extensional mode, as described in the IEEE Standard on Piezoelectricity (1987). Several piezoelectric, elastic and dielectric constants, as well as the corresponding electromechanical coupling factors, were plotted as a function of temperature ranging from 15°C to -165°C, up to 195°C and back down to 15°C. These material constants were obtained by analysing the fundamental resonance of the corresponding impedance or admittance spectra as a function of the frequency for each sample geometry and composition. Upon cycling the temperature between -165°C and 195°C, the piezoelectric constants d33 and -d31 , as well as the dielectric constants EpsT33, generally increased with temperature for both soft and hard PZT samples. However, the elastic constants sE11 and -sE12 exhibited abnormal variations seen as broad peaks over parts of the tested temperature range. These variations may be attributed to a tetragonal-to-rhombohedral phase change in the crystal structure of soft and hard PZT samples, occurring around 50°C and -75°C respectively. Furthermore, thermal hystereses were observed in all the studied material constants upon heating the samples to 195°C and during the subsequent cooling to 15°C. These hystereses were caused by de-pinning of domains in some cases and by irreversible contributions of domain dynamics during the first heating cycle in others. Finally, it was noted that, overall, the material constants of soft PZT varied significantly more than those of hard PZT under changing temperature conditions. This is due to the fact that the extrinsic contributions to the piezoelectric effect, caused by domain dynamics, are larger in soft PZT.

6170-16, Session 3

Time dependent evolution of polarization in PZT

J. E. Huber, Univ. of Oxford (United Kingdom); Q. Liu, Univ. of Cambridge (United Kingdom)

The dielectric and mechanical responses to a constant electric field have been measured on initially unpoled PZT-5H and PLZT 8/65/35. In particular, we are interested in the time dependent behavior of remnant strain and polarization and the results associated with the domain switching behaviour due to unipolar electric field. An experimental method has been developed to obtain the remnant strain and polarization by excluding strain gauge drift, leakage, dielectric and piezoelectric effects. The evolution patterns of the remnant strain and polarization in two soft ferroelectrics suggest that they undergo different microscopic polarization mechanisms. In PLZT 8/65/35, a critical remnant polarization was reached before rapid switching was observed, but no such threshold is observed in PZT-5H. Finally, thermal effects on the remnant strain and polarisation rates are reported. Possible rate laws are discussed.

6170-17, Session 3

Fatigue crack growth in ferroelectrics under cyclic electrical loading

A. Ricoeur, A. Emrich, M. Kuna, Technische Univ. Freiberg (Germany)

Today, piezo- and ferroelectric ceramics find a widespread application in adaptive systems. They are main components of actuator stacks and sensors or are integrated as fibers and laminated films into structural materials. Put into operation, they are mostly subject to cyclic loading by electric fields, mechanical loads or a combination of both. As with all brittle materials micro cracks have an essential influence on the reliability of the piezoelectric components. If an incipient macroscopic crack develops, the prediction of durability requires a fracture mechanics evaluation. Thereby, the mechanisms of fatigue crack growth in structural ceramics and ferroelectrics are basically different. Ferroelectric domain switching due to electrical and mechanical fields plays an essential role.

Crack growth under cyclic electrical loading has experimentally been investigated by different researchers. Thus, some qualitative knowledge on how the electric field intensity, cycling frequencies and signal shapes influence the crack growth rates is available. The subject of our paper is twofold. First, a geometry independent quantitative description of the phenomenon is given presenting an electromechanical crack growth rate relation similar to a Paris-Erdogan-Law. Therefore, experiments are evaluated in which fatigue cracks grow in Double-Cantilever-Beam (DCB) specimens made of PIC151 driven by cyclic electric loads. In some experiments the electric load is combined with a constant mechanical load. To quantify the loading at the crack tip, the electric displacement intensity factor KIV and the stress intensity factor KI are calculated numerically accounting for realistic electrical crack boundary conditions. The applicability of the K-concept in the presence of large-scale-switching is theoretically investigated and considered as justified to characterize the loading condition for fatigue crack problems. A method for a simplified calculation of the interaction integral for limited permeable cracks in piezoelectrics is presented. The numerical simulations reveal among others a crack closure effect leading to a threshold value of the electric load which is in good agreement with experimental observations.

Second, the crack driving forces which are due to domain switching are calculated. Therefore, a micromechanical model has been developed and implemented into a self-developed finite element code. A domain switching criterion is evaluated in representative volume elements deciding upon local changes of polarisation and inelastic strain. The influence of a rotation of the anisotropic material axes on the electrical and mechanical fields as well as the interaction of evolving residual stresses on the switching are taken into account. To demonstrate the reliability of the model, ferroelectric hysteresis loops are presented and discussed. Simulations of fatigue crack growth give information about the reason of electrically driven crack growth and enlighten the influence of different features such as poling state or loading history on the crack growth rate.

6170-18, Session 3

Understanding microstructural effects on long term electrical fatigue in multilayer PZT actuators

J. Mueller, S. A. Hooker, National Institute of Standards and Technology; D. Balzar, Univ. of Denver

Piezoelectric ceramics are desirable actuator materials due to their fast response, wide bandwidth, high force, compact size, and ease of motion control. Many new applications are emerging for these materials, including adaptive structures, vibration isolation, and nanorobotics. In these instances, the materials may be required to perform continuously over long durations, while also achieving maximum physical displacement. These demands translate into relatively harsh driving conditions, where an increased possibility of property degradation and fatigue exist. Microstructure control offers one possible route to improve fatigue resistance. To determine the relationship between microstructure and fatigue, we examined the effects of continuous cyclic actuation on multilayer lead zirconate titanate (PZT) actuators. These devices were produced from sub-micron particles and processed over a 150 ºC sintering range. The resulting actuators possessed average grain sizes from 2.5-4 microns. Components were fabricated in a surface mount configuration (0.30 cm x 0.15 cm) with ten active (PZT) internal layers, each 50 microns thick. Fatigue resistance was determined by monitoring the change in ferroelectric properties (remnant polarization, Pr, saturation polarization, Ps, and coercive field, Ec) during cumulative exposure to switching electric fields. Measurements were performed using a modified Sawyer-Tower circuit and applying a sinusoidal wave approximating the PZT-5A coercive field (Ec ~ 15 kV/cm). Microstructure evolution affected both the initial and fatigued properties of the different devices. All parts remained functional beyond 1E7 cycles, with no microcracking observed. Because of the dependence of the initial ferroelectric properties on sintering temperature, final polarization values were quite similar among all parts, indicating the retention of a minimum polarization regardless of microstructure. X-ray diffraction measurements were performed on as-produced, poled and electrically fatigued specimens. Examined crystallographic properties included coherently diffracting domain sizes evaluated from line broadening in the [001] and [100] directions, orientation ratio of c- and a-domains, and unit cell tetragonality. A possible clamping effect by smaller grain sizes of the spontaneous tetragonal distortion was found for processing temperatures below 1250 °C. This temperature seems to mark a threshold of the material, as specimens processed beyond this level showed only minor differences in crystallographic orientation, regardless of electrical treatment, indicating faster pinning of domains at higher, and facilitated domain wall movement at lower processing temperature. The results confirm measurements of electrical properties, which showed that devices processed at low temperatures fatigued far less than those processed at higher temperatures (< 20 % vs. \> 50 %), with fatigue rate increasing with increasing sintering temperature up to 1250 °C.

6170-19, Session 3

Development of broadband, high-power single crystal sonar transducers

H. Robinson, Naval Undersea Warfare Ctr.; J. Powers, Progeny Systems Corp.; M. B. Moffett, Anteon Corp.

Ferroelectric single crystal materials have been developed under the auspices of the Defense Advanced Research Projects Agency and the Office of Naval Research for use in sonar and ultrasonic arrays. Single crystals such as lead magnesium niobate-lead titanate (PMN-PT) typically have elastic moduli of 10-15 GPa, piezoelectric constants of 1200-2000 pm/V and electromechanical coupling factors of 0.9. These unique material properties promise a revolutionary advance in sonar and ultrasonic technology. In particular, single crystal sonar projectors can be designed that offer over an octave of bandwidth from a single transducer, substantially increased source level over current ceramic transducers, smaller size and reduced power amplifier requirements. Several prototype single crystal transducers and arrays have been developed for Naval applications whose performance demonstrated conclusively that the enormous potential of these materials can be realized in practical devices. The first demonstration was an array of sixteen longitudinal vibrator (tonpilz) transducers. Extensive testing of this array revealed that many properties of the array's performance varied depending on the magnitude of the dc electrical bias and ac electrical drive. However, it was also discovered that these performance variations correlated exactly with the variations in the measured material properties observed in laboratory material characterizations. This tonpilz array showed an improvement by a factor of three in bandwidth over a comparably sized system using lead zirconate titanate (PZT) ceramic transducers, with as much as 15 dB higher source levels (or 30 times the acoustic power) available within that band. These improvements occurred with no increase in the drive amplifier size, indicating the tremendous performance improvements pos-

sible when ferroelectric single crystal transducers are used in place of PZT ceramic ones. A second device demonstration was a compact, high power single crystal cylinder. This transducer showed very small impedance variations (3:1) over nearly a decade of frequency. Simultaneously, this transducer was extremely well matched to the power amplifier, with a tuned power factor of 0.8 or more, over 2.5 octaves of frequency. This implies that the amplifier that is needed to drive this transducer can be physically smaller in size, simpler to design and cheaper to build than an analogous ceramic based system designed to cover the same frequency band. [Work sponsored by DARPA and ONR]

6170-20, Session 3

Characterizing reliability in multilayer PZT actuators

S. A. Hooker, National Institute of Standards and Technology

Many new applications are emerging for piezoelectric ceramics including adaptive structures, active flow-control devices, and vibration and noise suppression. Additionally, there are opportunities to use these devices in the biomedical field for miniature pumps, ultrasonic surgical tools, micro-needle arrays, and nanorobotics. In each of these instances, actuator stability is critical, representing a significant challenge for piezoelectric ceramic materials. For example, the properties of lead zirconate titanate (PZT) have been found to degrade, often significantly, during continuous operation due to a combination of domain pinning, relaxation of interfacial stress, and, in the worst cases, micro-crack formation. This degradation, referred to as actuator fatigue, can be even more pronounced when high voltages are used to achieve maximum displacement. Multilayer configurations, such as co-fired stacks, are important for many emerging applications, particularly as these devices are now being produced in very small physical dimensions with lower power requirements. However, multilayer components may also be highly susceptible to long-term fatigue due to the large number of interfaces involved in their configuration. In this work, we report the polarization and displacement fatigue for a series of miniature (3 mm x 3 mm x 2 mm) multilayer actuators produced commercially from soft PZT (PZT-5A-type) materials. These devices have relatively thin internal layers (~ 50 microns), substantially reducing the voltage needed for operation. Frequency, voltage, and clamping force were varied to determine their effect on the rate of fatigue. This presentation will describe the significance of these parameters on determining actuator reliability, with the goal of ensuring that application developers optimize operational conditions to promote fatigue resistance.

6170-21, Session 3

Low-voltage single crystal actuators

X. S. Jiang, P. W. Rehrig, J. Luo, W. S. Hackenberger, TRS Technologies, Inc.

Conventional co-fired PZT actuators are used extensively in Piezoelectric actuations requiring low driving voltages because of the fact that full strain could be achieved under < 100 V for PZT tape thickness of less than 50 um. However, piezoelectric properties of PZT is low comparing with single crystals, and PZT lost ~ 70% of its room temperature piezoelectric activity at temperature of 77K, indicating that low voltage PZT actuators are not desired for applications featuring with low profile, and/or low temperatures. On the other hand, single crystal piezoelectrics has drawn a lot of attention for high strain piezoelectric actuations because of its high piezoelectric coefficient, electromechanical coupling coefficient and energy density. But the relatively high driving voltage is required to achieve full strain for single crystal actuators with regular layer thickness of 0.5 mm, which could also lead to bulky driving electronics and that is not allowed in some cases. In this paper low voltage single crystal actuators will be investigated using thin PMN-PT plates for applications requiring low voltage, large strain, low profile and/or actuation at cryogenic temperatures. Firstly, single crystal thickness effect on piezoelectric properties was studied by investigating the relationship between electromechanical coupling coefficient of PMN-PT crystals and the crystal thickness. It is found that electromechanical coupling coefficient (kt) of 50 um, 75 um and 100 um PMN-PT single crystal thin plates are 0.5, 0.51, and 0.55, respectively, which are slightly lower than that of bulk single crystal (0.6). A couple of single crystal actuators were then assembled using crystal plates with thickness of 100-250 um. These actuators were characterized by measuring strain vs. electric field at room temperature and cryogenic temperatures. A 3 mm x 3 mm x 19 mm single crystal stack actuator showed 21 um stroke at room temperature under 150 V, and 10 um stroke at 60 K under 200 V. A 5 mm x 5 mm x 12 mm single crystal actuator showed 13.5 um stroke at room temperature under 150V, and 6 um stroke at 77K under 150V. These low voltage actuators hold promising in space precise positioning and adaptive structures and cryogenic SEM, SPM and STM applications.

6170-22, Session 3

Advanced Tonpilz transducers incorporating single crystal piezoelectrics

K. A. Snook, P. W. Rehrig, W. S. Hackenberger, X. S. Jiang, TRS Technologies, Inc.; R. J. Meyer, Jr., D. C. Markley, The Pennsylvania State Univ.

Transducers incorporating the single crystal piezoelectric Pb(Mg1/3Nb2/3)x-1TixO3 (PMN-PT) exhibit significant advantages over ceramic piezoelectrics such as PZT, including both high electromechanical coupling (k33 \> 90%) and piezoelectric coefficients (d33 \> 2000 pC/N). This orientation gives inherently larger bandwidth and output power, however, the anisotropy of the crystal also allows for tailoring of the performance by orienting the crystal along different crystallographic axes. This attribute can be used to improve thermal or mechanical stability, which is important in high power, high duty cycle sonar applications.

By utilizing the '31' resonance mode, the high power performance of PMN-PT can be improved over traditional '33' mode single crystal transducers, due to an improved aspect ratio. Utilizing novel geometries, effective piezoelectric constants of -1000 pC/N to -1600 pC/N have been measured. The phase transition point induced by temperature, pre-stress or field is close to that in the '33' mode, and since the prestress is applied perpendicular to the poling direction in '31' mode elements, they exhibit lower loss and can therefore be driven harder.

The high power characteristics of tonpilz transducers can also be affected by the composition of the PMN-PT crystal. TRS modified the composition of PMN-PT to improve the thermal stability of the material, while keeping the loss as low as possible. More than a 50% decrease in the temperature dependence of the dielectric constant was achieved, while maintaining a loss mechanical loss below 0.008. A decrease in the source level of approximately 5 dB was calculated, which can be compensated for by the higher drive voltages possible.

6170-11, Session 4

Mixed mode elastic-magnetostrictive wave propagation in a cubic media

W. D. Armstrong, Univ. of Wyoming

A preliminary theoretical effort has provided a robust three dimensional energy based model of magnetostrictive wave propagation in a general cubic magnetostrictive material. Under high intensity impact the present theory predicts that the wave front will split between a higher velocity elastic precursor wave and a lower velocity, strongly dissipative, magnetostrictive shockwave. The wave front solution strongly depends on longitudinal pre-stress level and initial magnetization state. We may expect that a significant portion of the magnetostrictive shockwave deformation will be reversible under sufficiently large external applied magnetic fields. In combination these technical characteristics therefore present an opportunity to develop magnetostriction based shock hyper-toughness in safety critical civil and military structures.

6170-12, Session 4

High-temperature plasticity of polycrystalline Galfenol (Fe-Ga)

L. M. Cheng, R. Ham-Su, Defence R&D Canada - Atlantic (Canada)

Magnetostrictive Galfenol (Fe-Ga) is a promising and mechanically robust actuator material. Single crystals of Galfenol have been shown to exhibit up to 400 ppm magnetostrictive strains with saturating fields of several hundred oersteds. However, due to the high conductivity of Galfenol, device operation will require it to be laminated, or in thin sheet form, in order to avoid eddy current loses. Current lamination techniques are costly, time consuming, and can only produce a small number of laminates at a time. To produce large quantities of thin sheet Galfenol for future device applications, we are investigating the effects of rolling on texture evolution and magnetostrictive properties of polycrystalline Galfenol. This work includes experimental rolling, theoretical modeling and studies of high temperature polycrystalline plasticity. Models are being developed for the microstructure evolution and texture development as the deformation process proceeds. In-situ neutron diffraction experiments are being used to attain quantitative information on the high temperature, plane strain deformation of Galfenol. These experiments are also used to identify preferential slip systems and thermomechanical treatments that will enhance/minimize lattice rotation during deformation. The high-temperature plasticity and deformation behavior of polycrystalline Galfenol during simulated rolling conditions is also being studied. The results obtained from these experiments are critical to the development of the models which take into account the relations among imposed deformation strain, constraints between neighboring grains and operating slip systems. Recovery and recrystallization mechanisms

and kinetics are also being studied. As shown by these experiments, significant dynamic recovery and recrystallization occurred during the deformation process. In this paper, latest results from these investigations will be discussed.

6170-13, Session 4

Effect of stress annealing on Galfenol and Alfenol magnetostrictive alloys

A. E. Clark, Clark Associates Inc; J. B. Restorff, M. Wun-Fogle, Naval Surface Warfare Ctr.; E. M. Summers, ETREMA Products, Inc.

Selected Etrema Produced Galfenol (Fe100-xGax, x = 6, 12.5, 17, 18.4) and Alfenol (Fe85Al19) research grade alloy rods (~50mm x 6 mm dia.) were annealed under stresses up to 200 MPa at temperatures ranging from 100ºC to 700ºC for periods of 10 and 20 minutes. Because of the magnetostriction of the alloys, such heat treatments build in various degrees of uniaxial magnetic anisotropy depending upon annealing stress, annealing temperature, and alloy composition. This built-in uniaxial magnetic anisotropy has the effect of extending the high power capability of these positive magnetostrictive alloys into operation under tensile loads.

Magnetization and magnetostriction measurements of both annealed and unannealed alloys have been taken at room temperature under compressive loads \> 100 MPa to tensile loads up to 50 MPa (~7 ksi). To fit the magnetization and magnetostriction as a function of magnetic field, an energy expression containing a fourth order anisotropy term (cubic term) plus a second order uniaxial term was utilized. To fit the data over a wide range of (compressive) stresses it was necessary to include a second order uniaxial stress dependent term. The uniaxial anisotropy now consists of two parts: (1) the conventional term that depends upon the annealing stress and independent of the applied (compressive) stress and (2), a new term that linearly depends upon the applied (compressive) stress. Using this energy expression excellent fits were obtained to the magnetization curves and magnetostriction curves. Importantly, from the magnitude of the constant 'C', which is derived from the stress dependent anisotropy term, it is possible to calculate the maximum tensile stress that can be built-in by stress annealing.

6170-14, Session 4

Magnetostriction of polycrystalline strong-textured Fe-17at%Ga fabricated by combining rapid-solidification and sintering processes

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Magnetostrictive bulky Fe-17at%Ga alloy was fabricated by combining laminate of rapid-solidified ribbons (80 μm in thickness) and spark plasma sintering/joining (SPSJ). SPSJ is characterized by short time and low temperature heating and sintering process. The laminated sample made by SPSJ maintained the unique metallurgical microstructure of polycrystalline texture of columnar grains as well as almost non-equilibrium metastable phase with little existence of ordered precipitations in as-spun ribbons. The excellent sintered sample having large magnetostoriction was obtained under a condition of the compressive stress of 100 MPa at the temperature of 973 K. The magnetostriction depended on compressive pre-stress level for specimen and reached about 100 ppm which was a half of value obtained for the ribbon sample. Furthermore, by following short annealing for this specimen, the magnetostriction increased to 170 ppm comparable to the ribbon's value.

6170-23, Session 5

A free energy model for the magnetostrictive behavior of polycrystalline Iron-Gallium alloys

J. Atulasimha, A. B. Flatau, Univ. of Maryland/College Park

While study of single crystal FeGa alloys is a good starting point for characterizing and modeling Galfenol behavior, commercial actuators and sensors are more likely to be made of polycrystalline FeGa. This is due to greater yields produced by manufacturing process used to make polycrystals which could make FeGa commercially viable, provided the actuation and sensing properties of polycrystals are not significantly inferior to that of single-crystals. This motivates the study of the effect of presence of <110\> and <111\> crystallographic orientations in polycrystal samples in degrading its performance relative to that found in oriented <100\> single crystal alloys.

The behavior of 18.4% Ga polycrystalline samples produced by Free Stand Zone Melt (FSZM) manufacturing processes will be characterized while properly addressing inherent statistical variations in the polycrystalline samples. This effort will consist of characterizing the actuation and sensing behavior these samples by subjecting them to quasi-static constant compressive load tests and constant applied field tests respectively.

The sample texture will be determined using Electron Back Scattering Diffraction of multiple sample cross-sections. In addition to establishing empirical correlations between texture and actuation and sensing behavior, an effort will be made to incorporate texture information in a model that captures the net effect of the distinct <100\>, <110\> and <111\> contributions to actuation and sensing behaviors.

6170-24, Session 5

Measurement of magnetic field dependent Young's modulus of Iron-Gallium alloy in flexural mode

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Iron-Gallium alloy (Galfenol) is a promising magnetostrictive material owing to its moderate saturation magnetostriction at low applied magnetic fields. It has shown high magneto-mechanical coupling along with attractive elastic properties that would enable it to be used as a smart structural material. Unlike the brittle magnetostrictives which can be only used in the axial compression mode, Galfenol's structural properties enable it to be used in axial tension and bending thus opening up new application areas for its use as magnetostrictive sensors and actuators and hence demanding the characterization of its elastic properties in flexural mode. Due to the inherent magneto-mechanical coupling, the elastic properties of a magnetostrictive material are dependent on the magnetic state of the material. A four-point bending test was devised based on ASTM standard C 1161. To expose the Galfenol sample to a magnetic field, the test setup was modified to accommodate a closed magnetic circuit made up of a source of magnetic field provided by a solenoid, an electromagnet core made of 1018 steel and the Galfenol sample. The magnetic field was applied along the length of the sample by using a controlled current source. The current was varied from 0 to 2.5 A which corresponded to a change in magnetic field of upto 79.6 kA/m in the air inside the solenoid. From previous work, this field was deemed to be sufficient to magnetically saturate the Galfenol sample. A finite element model was used in the design of the magnetic circuit to ensure minimum flux leakage from the circuit and to verify the homogeneity of the magnetic field inside the Galfenol sample. The polycrystalline Galfenol samples used were supplied by ETREMA(c). The samples had a nominal composition of 16 at % gallium and 84 at % iron and were classified as research or production grade based on their production process. The samples were of the dimensions 25mm x 2mm x 1.5mm with a preferential <100\> texture along the length of the sample. An MTS 810 universal testing machine was used to apply the load and the stress on the sample was calculated from analytical expression. A strain gage attached on the sample was used to obtain the strain along the length of the sample. A pickup coil wound around the sample in conjunction with an integrating fluxmeter was used to record the changes in magnetic induction in the sample. Experiments were performed under different applied magnetic fields until the sample saturated. Results will be shown for the stress-strain plots obtained for each material under different applied magnetic fields and the corresponding Young's modulus calculated from the slope of these plots.

6170-25, Session 5

Machining of Iron-Gallium for microactuator

T. Ueno, T. Higuchi, The Univ. of Tokyo (Japan); E. M. Summers, ETREMA Products, Inc.

We have succeeded fabrication of micro magnetostrictive actuator using Iron-Gallium. Iron-Gallium is a machinable magnetostrictive material with moderate magnetostriction of 300ppm. The actuator consisting of rod of Fe-Ga and winding coil is expected to have advantage of smaller size, low voltage and non-contact driving and higher efficiency compared with that of PZT. In this paper, we discuss the machining condition of the material and how it affects on the magnetostrictive properties. The experimental result of displacement with different frequency of driving is shown to investigate eddy current effect.

6170-26, Session 5

Performance and application of novel magnetic actuator using composite of Terfenol-D and PZT

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Novel composite of Terfenol-D and piezoelectric actuator was proposed for coilless magnetic force control. This force control is based on the inverse magnetostrictive effect of magnetostrictive materials whereby the strain hence magnetic force is controlled by the actuator. Because the piezoelectric actuator is an electrically capacitive, this method has the advantages of zero power consumption in steady-state operation. Furthermore, the configuration which requires no robust structure of constraint is simple compared with that of conventional device. In this paper, the behavior of the magnetic force dependant on the dimension of the magnetic circuit (permanent magnet) and pre-stress is investigated. Applications of magnetic levitation and linear stepping motor are also constructed to demonstrate its advantage of zero power consumption.

6170-27, Session 5

Enhanced GMI effect in Fe73.5-xMnxSi13.5Nb3Cu1 (x = 1, 3, 5) nanocomposites for sensor application

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Giant magneto-impedance (GMI) sensors has greatly benefited from the development of advanced sensing materials. Our recent works have revealed that substitution of Cu and Nb for B in an initial Co70Fe5Si15B10 composition forming the Co70Fe5Si15Nb2.2Cu0.8B7 composition improves both giant magnetoimpedance (GMI) effect and its field sensitivity [1]. Similar feature has also been reported on Fe73-xAlxSi14B8.5Cu1Nb3.5 nanocrystalline ribbon with Al (x = 2) substitution for Fe [2].

In the present work, we have investigated the giant magnetoimpedance (GMI) effect in Fe73.5-xMnxSi13.5Nb3Cu1 (x = 1, 3, and 5) nanocomposites. The nanocomposite microstructures were attained by annealing the rapid quenched amorphous ribbons. GMI was measured as functions of magnetic field, frequency and ac driving current. The results indicate that the GMI ratio [Z/Z(%)] increased with increasing Mn-substituting content as a direct consequence of the increase of the ultrasoft magnetic properties. With increasing frequency, the GMI ratio first increased up to f = 2 MHz and then decreased at higher frequencies. At the frequency of 2 MHz, the GMI ratio reached the highest values of 83%, 94% and 130% for x = 1, 3, and 5 compositions, respectively.

It was found that, for the samples investigated, the GMI effect and its sensitivity to the applied magnetic field increased with increasing ac driving current (see figure, for x = 5, and the insert). Interestingly, the field sensitivity of GMI shifted towards a higher frequency as the ac driving current was increased, which is ideal for high-frequency GMI sensor applications. This phenomenon is correlated to the ac current dependence of longitudinal permeability in connection with the dc magnetization data.

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6170-28, Session 5

Effect of the processing conditions on the microstructure of urethane magnetorheological elastomers

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Magnetorheological (MR) materials change their rheological properties under the influence of applied magnetic field. Magnetorheological elastomers (MREs) are solid analogues of magnetorheological fluids. They both consist of micron sized magnetically permeable particles in non-magnetic matrix material. In a similar way as in the case of MR fluids, the particles try to arrange themselves in the direction of magnetic field.

MR fluids have a field-responsive yield stress. When an external magnetic field is applied, MRFs undergo a considerable increase in their apparent yield stress. MRFs have some disadvantages like the inability of ferromagnetic iron particles to remain in suspension. Also, it is possible that irreversible agglomeration of the particles used may reduce fields of their practical applications.

The advantage of MRE, in regard to MR fluids, is that ferrous particles don't undergo sedimentation. The thermal stability of MRE is grater than MRF and their resistance for degradation is higher. In the comparison with MR fluids the MR elastomers have a field-responsive modulus. The amount of particle filler can also be lower in MRE comparing to MRF. As a result the weight of sensing and actuating devices based on MREs is lower. Due to the characteristic MRE microstructure the time of response and strain value versus magnetic field intensity could be shortened. Interest in such intelligent materials has increased recently. They hold promise in enabling variable stiffness devices and adaptive structures in aerospace, automotive, civil, electrical engineering applications.

The MRE based on polyurethanes and silicone rubbers were made and studied. The aim of this study was to develop an innovative processing method of magnetorheological elastomers. This method comprises optimization of the MRE structure in the context of their properties in magnetic field. The MRE were manufactured by dispersing magnetic particles in a polyurethane matrix. The influence of the amount of the ferromagnetic particles, spacing between them and their arrangement in relation to the external magnetic field was investigated. Influence of particles size and shape on the properties was also analysed.

As matrixes several different elastomers with different stiffness were used. Their properties were compared with the commercial available silicone rubbers. Relative change of the MRE modulus in the magnetic field is higher in the case of soft elastomers. Urethane elastomers are very promising as MREs matrix, because they are more heat resistant and have much better degradation stability comparing to natural and silicone rubbers. The high iron volume fraction may influence the long-term stability of the MRE. The selection of suitable matrix material is important when cosidering the possible applications and long-term stability of MRE.

It was found that the structure of the MRE produced depends on the viscosity of the matrix before curing and the flux density of the magnetic field applied. Two different magnetic field strengths were used: 100 and 300 mT. The amount of the carbonyl iron particles was equel to 1.5, 12.0 and 33.0 vol. %. Scanning electron and light microscopy techniques were used for the MRE microstructure observations. The compression tests on cylindrical samples in the absence and presence of a magnetic field showed that the magnetic field increase the stiffness of the material.

6170-29, Session 5

A particle pair model for magnetorheological fluids

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A microstructural model of the motion of particle pairs in MR fluids is proposed that accounts for both hydrodynamic and magnetic field forces. A fluid constitutive equation is derived from the model that allows prediction of velocity and particle structure fields. Results for simple shear and elongational flows are presented for cases where particle pairs remain in close contact so they are hydrodynamically equivalent to an ellipsoid of aspect ratio two. Additionally, only the magnetic force component normal to the vector connecting the centers of a particle pair affects motion. Shear flow results indicate particle pairs rotate continuously with the flow at low magnetic fields while a steady state is reached at high fields. For elongational flows, when the applied magnetic field is parallel to the elongation direction, particle pairs orient in the field/flow direction. Either orientation is possible when the field is perpendicular to the flow.

Model predictions for various shear rates and magnetic fields are compared with experimental data. The comparison indicates a good agreement between model predictions and experimental data at low to moderate shear rates and magnetic fields.

6170-30, Session 5

Magnetorheological elastomers: studies of fatigue, temperature, and particle size dependence

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Magnetorheological elastomers (MREs) are state-of-the-art elastomagnetic composites comprised of magnetic particles embedded in an elastomer matrix. MREs offer enormous flexibility given that elastomers are easily molded, provide good durability, exhibit hyperelastic behavior, and can be tailored to provide desired mechanical and thermal characteristics. MRE composites combine the capabilities of traditional magnetostrictive materials with the properties of elastomers, creating a novel material capable of both highly responsive sensing and controlled

actuation in real-time. While a cache of literature exists quantifying and modeling MRE behavior, several issues central to the materials science and rheology of elastomers have not been fully addressed in MREs. First, being crosslinked macromolecular networks, elastomers exhibit temperature dependent behavior. Second, filled elastomers are subject to cyclic damage, e.g. the Mullin's effect. And third, both the transient and damage responses of elastomers are known to be functions of particle size distributions. This study seeks to address these core issues in relation to MREs using static and dynamic mechanical testing, and magnetometry techniques over a range of temperatures. In addition, a novel method of increasing the critical particle volume concentration to enhance the MR effect beyond its suspected limits is introduced.

6170-31, Session 6

A time-integration scheme for thermomechanical evolutions of shape-memory alloys

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This Paper addresses the thermomechanical simulation of structures embedding Shape Memory Alloys (SMA). Those materials have been extensively studied in the context of quasi-static evolutions, supposing that the system is in thermal equilibrium at each time. The phase transformation in SMA is known to produce heat (recoverable latent heat and irreversible frictional contributions), and the validity of the thermal equilibrium assumption is in fact dependent on the rate of loading and on the thermal exchange conditions between the system and its environment. To better predict the response of SMA systems, it is therefore necessary to take the thermomechanical coupling into account, considering the temperature field as an unknown to be solved for. Several material models have been proposed in that direction (Souza et al. 1998, Anand and Gurtin 2003, Petrini and Auricchio 2004). The resulting evolution problem is nonlinear and exhibits strong coupling between the mechanical and temperature fields. The time-discretization of this system is not obvious, and difficulties of convergence have been observed in numerical simulations (Pagano and Allard 1999). The purpose of this Paper is to propose a time-discretization scheme for which convergence is ensured for a large class of SMA material models, thus allowing for robust numerical simulations of thermomechanical evolutions in SMA structures. A central point in the analysis is the experimental fact that, for SMA, the irreversible heat contribution, which is connected to the mechanical dissipation, is small compared to the latent heat contribution (Chrysochoos et al. 1995). This leads to a simplification of the heat equation in the rate evolution problem. A time-integrated version of the corresponding thermomechanical problem is proposed, allowing the mechanical and temperature fields at time t' to be computed from their values at time t. This incremental scheme is a discretization of the rate problem in the sense that it coincides with the rate evolution problem as t' tends to t. The key feature of the scheme proposed is that its solutions can be expressed as the solutions of a variational problem. This variational formulation allows one to study the existence and unicity of solutions to the finite-time increment thermomechanical problem. In particular, focusing on the superelastic regime, existence of solutions is proved for some of the thermomechanical constitutive laws proposed recently in the literature. The approach presented is applied to simulate the propagation of a martensitic zone in a circular cylinder under traction. Initially the structure is fully austenitic. As the loading increases, transformation into martensite takes place. The time histories of the phase transformation and of the temperature field, as computed with the finite-time increment scheme proposed, are studied. This example is also used to discuss the influence of the thermomechanical coupling as well as the robustness of the method proposed.

6170-32, Session 6

Behavior of a hybrid constitutive model for shape memory alloy micro-actuators

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The volume and weight budgets in missiles and gun-launched munitions have decreased with the military forces' emphasis on soldier-centric systems and rapid deployability. Reduction in the size of control actuation systems employed in today's aerospace vehicles would enhance overall vehicle performance as long as there is no detrimental impact on flight performance. Functional materials such as shape memory alloys (SMA's) offer the opportunity to create compact, solid-state actuation systems for flight applications by virtue of the material's ability to convert electrical energy to thermal energy to mechanical energy within its microstructure. A hybrid SMA model was developed for designing micro-actuated flow effectors. It was based on a combination of concepts originally presented by Likhatchev for microstructural modeling and Brinson for modeling of transformation kinetics. It was assumed that, under stress, only one of the three martensite variants oriented along the local cartesian grain coordinate system could develop according to a maximum stress criterion. The variant strain was calculated with the classic Bain deformation tensor. Transformation of stress-induced or autoaccomodation martensite was described using the kinetic model that Brinson developed for a modified Tanaka constitutive law. Global strain of the polycrystal, where the grains were assumed to be randomly oriented, was calculated by averaging the elastic, stress-induced and autoaccomodation strains of each grain over the total material volume. The phase diagrams for a series of SMA wires varying between 0.002" to 0.005" dia. were created by carrying out tensile tests in a Rheometrics RSA-II solids analyser over a range of temperatures from 30C to 130C. The characterization parameters were used in the hybrid model to predict the displacement-time trajectories for the wires under constant load conditions. Predictions were compared with experimental measurements from a LVDT-equipped testbench. A second testbench was constructed to study the performance of the wires in an antagonistic micro-actuator set-up. The force of each wire was measured with thin beam load cells and the displacement was measured indirectly by a LVDT through a pulley mechanism. A series of step voltage inputs were alternately injected into each wire of the two-wire antagonistic actuator to characterize the peak to peak displacement and the motion time constant. The hybrid SMA model was used as part of a Matlab antagonistic SMA model to predict the testbench data. The full paper will discuss the results of the validation and design effort.

6170-33, Session 6

Modeling and testing of shape memory alloy chiral honeycomb structures

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In this work we develop numerical models and tetsing procedures to assess the in-plane mechanical properties of chiral honeycomb structures made out shape memory alloy ribbons. The chiral structures feature an auxetic behaviour - i.e., a negative Poisson's ratio effect, with global epansion when the samples are pulled along one direction. The chiral honeycombs are made with superleastic Ni46Ti48Cu6 ribbons connected to hard PVC cylinders. The samples are accomodated in special designed rigs to measure the in-plane mechanical properties (in-plane stiffness and Poisson's ratios). Numerical homogenisation FE models based on Auricchio and Taylor model (SPIE Paper 2779) are developed to simulate the in-plane stress-strain curves and the strain dependence of the Poisson's ratio. The sumulations and the experimental results provide good comparison. In particular, the Poisson's ratios shows a degree of constancy (around -1) well above 20 % of tensile strain deformation, in agreement with other theoretical results related to chiral structural cellular solids. The overal results show the potential of chiral honeycombs for strain energy storage, crashworthiness capabilities and implementation in morphing and deployable structures.

6170-34, Session 6

Is it necessary to model shape memory alloys within the scope of large strains?

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Shape memory alloys (SMA) can undergo phase transformations between a higher-ordered austenite phase and a lower-ordered martensite phase as a result of changes in temperature and the state of stress. Consequently, SMA exhibits several macroscopic phenomena not present in traditional materials.

Three significant phenomena are the shape memory effect, the external two way effect as well as the phenomenon of pseudoelasticity.

These unique features of SMA have found numerous applications in mechanical, automotive, aerospace and electronic industries as well as in the field of medical technology.

The increasing use in commercially valuable applications has motivated a vivid interest in the development of accurate constitutive models to describe the thermomechanical behaviour of SMA.

Meanwhile, many three-dimensional material models have been developed to describe the behaviour within the frame of small deformations.

Some of these describe only the effect of pseudoelasticity [1],[2] whereas others consider also the shape memory effect [3],[4].

However, there is still a lack of material models which are developed in the scope of large strains [5],[6].

In this contribution we present a thermomechanically coupled material model for SMA based on the concept of Helm & Haupt [7] which includes the effect of pseudoelasticity as well as the shape memory effect and the external two way effect.

Experiments show that SMA materials exhibit deformations up to 20% strain if one takes into account the plastification phase which follows the austenite-martensite transformation.

For this reason we extend the latter model [7] within the scope of large strains.

Subsequently, the model is implemented into a FE code by using an innovative implicit time integration scheme.

The final aim of the research work is to investigate whether FE simulations of SMA applications, e.g. NiTI-stents and medical foot staples, should be based on large strain formulations.

If this was not the case the computational cost of such numerical investigations could be reduced significantly.

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6170-35, Session 6

Modeling the essential atomistic influence in the phase transformation dynamics of shape memory materials

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A physics based modeling framework to analyze the dynamics of multivariant phase transformation in three-dimensional samples of shape memory materials have been developed recently by these authors. The present paper is focused on linking the previously developed microscopic model with the atomistic reordering process that gives rise to self-accommodating microstructure. The microscopic model is based on a systematic representation of the Gibbs free energy in stress, temperature and n-dimensional order parameter space. Here n indicates the number of martensitic variants (M). Landau theory has earlier been successfully applied to solve the problem of phase-field evolution in phase transforming solids. In the context of diffusionless transformation in solids described by the Landau theory of first-order kinetics, the order parameters are the scaled ensemble averages of the atomic order variables. The diffusion kinetics model based on the time-dependent Ginzburg-Landau equation is thus the homogenized form of the spatio-temporal fluctuation due to atomic reordering. Our main objective in this paper is to study how this first-order kinetics influences the stress-temperature induced dynamics of phase transformation in microscopic and larger length-scales without attempting to solve a molecular dynamic problem in a coupled manner. This idea leads us to a thermodynamic conservation law whose characteristics are controlled by the phase kinetics. Numerical results show how this model captures the sharp interfaces and hysteretic cycles. However, while employing such microscopic model in predicting the response over large time-scales, one requires appropriate dislocation mechanisms to be accounted for. For this we turn back our attention to the dynamics of atomic ensamble by considering small clusters across grain boundaries. Depending on the

microscopic state in stress-temperature space, we introduce random dislocations in the lattice structure and then employ a Density Functional Theory (DFT) to couple the dynamics of the clusters with the macroscopic model. This coupling is implemented over discrete spatio-temporal scales in order to update the microscopic model. Numerical simulations are reported for small samples with prescribed grain-boundaries. Comparison between thermo-mechanical shake-down of Ni-Al, Ni-Ti and Ni-Cu-Al alloys are reported.

6170-36, Session 6

Experimental test for numerical simulation of SMA characteristics and its simulation

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Shape memory alloys(SMA) are metal alloys, which exhibit unique properties, that is, pseudo-elasticity, one-way shape memory effect(SME) and two-way shape memory effect(TWSME). SMA can exhibit interesting features such as diverse responses according to the induced temperature and stress. SMA changes its properties and material behavior progressively under cyclic loading conditions and finally reaches stable path(state) after a certain number of stress/temperature loading-unloading cycles, so called 'training' completion. The presence of permanent deformation, due to plastic strains or residual martensite variants during the material training, shifts the material characteristic curves of SMA wire.

Through the training and two-way experiments, SMA wire accumulates drastic permanent (irreversible) deformation until experiencing about 50~100 cycles. After 300 training cycles, SMA wire is to be in a stable state. In this study, we measured its stress-strain curve in stable state. In addition, we observe other important effects such as effect of stress induced during training, time rate of thermal cycle, etc. until now, time rate of thermal cycle is not considered significantly and only extremely slow time rate is considered in most SMA experiments and used in SMA behavior simulations. Therefore to make the actuators using an SMA wire which has the fast response or short-time thermal cycle, these effects should be properly considered.

From the result of two-way experiment at each (short or long time) cycle in phenomenological aspect, stress-strain-temperature relations and hysteresis characteristics become changed. In short-time cycle, strain-temperature curve moves in counterclockwise and the size of hysteresis envelop is large. As the time rate of the thermal cycle increases, the size of the hysteresis envelop is getting smaller and strain-temperature curve moves along the clockwise direction above a certain cycle time. Above that thermal cycle time, hysteresis is fixed in the stable state. These new effects of SMA are investigated and the effect would be explained qualitatively.

The present work presents the experimental test using 1-D SMA wire through two-way shape memory effect after training by thermal cycling. Through these tests, we measured the characteristics of SMA. With the estimated SMA properties and effects, we compare the experimental results with the simulation results based on the SMA constitutive equation which is advanced ones including the training, thermal rate effect, etc.

6170-37, Session 6

Properties of a high-temperature NiTiPd shape memory alloy in tension and compression

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The numbers of specific designs and potential applications involving high-temperature shape memory alloys have been growing in recent years, yet available materials for actual implementation in such plans are limited. Even in those cases where promising new high-temperature shape memory alloys have been identified, the knowledge base for such alloys contains gaps crucial to the development and implementation of these materials in actuation and other applications.

We begin to address these issues by characterizing the mechanical and shape memory behavior of a Ni-30Pd-50.5Ti high-temperature shape memory alloy in both uniaxial tension and compression. Isothermal tensile and compression tests were performed on the NiPdTi alloy in the martensitic and austenitic states. While superelastic behavior was not observed, a stress induced martensite was produced when the alloy was tested just above the austenite finish temperature. This stress induced martensite was not reversible upon unloading but could be recov-

ered by additional thermal input. Since the elastic modulus of the material was very dependent on strain level, dynamic Young's Modulus was determined as a function of temperature by an ultrasonic technique.

Additionally, the performance of a thermally activated actuator material is dependent on the work output of the alloy; therefore, the paper emphasizes this performance index. The strain-temperature response of the alloy under various loads was determined in both tension and compression and the specific work output calculated and compared in both loading conditions. Interestingly, the strain-temperature response and specific work output were similar for tension and compression loading. In both cases the strain-temperature loops did not close at the low temperature end of the hysteresis due to the fact that the transformation strain during cooling was always larger than the transformation strain during heating. This was the result of permanent plastic deformation of the martensite phase with each cycle. Consequently, before this alloy can be used under cyclic actuation conditions it would be necessary to modify the microstructure or composition of the material in order to increase the resistance of the alloy to plastic or permanent deformation.

6170-38, Session 6

A comparison of the DSC measurements of shape memory alloys and the material's thermal characteristics in a large scale actuators

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An accurate measure of a Shape Memory Alloy's (SMA) transition temperatures is necessary for the development of successful actuator designs. Differential Scanning Calorimetry (DSC) is used to obtain SMA's transition temperatures associated with changes in alloy formulations, fabrication processes, and forming methods, and to predict an SMA's thermal characteristics when designed into an actuator. However there is little data directly correlating a material's DSC results with its performance in an actuator configuration, particularly for large-scale actuators producing high force and large displacements. In this paper the authors compare the DSC results of several NiTinol samples with the thermal performance of the same material in a rotary actuator. Data are presented for NiTinol torque tubes 5.5" long by 0.4" in diameter. The tubes were tested over a range of loads exceeding 150 in-lbs of torque, with angular displacements of more than 60 degrees, and for durations exceeding 7,000 thermal cycles. Data from various NiTinol suppliers, levels of cold work, and a range of heat treatments is presented. The DSC data is directly compared to the strain vs. temperature hysteresis curves of the same material under various loads; both before and after extended cycling. The value of the DSC measurements as a predictor of a material's thermal characteristics in an actuator configuration is assessed. Additionally the DSC measurement of SMA parts formed using Vacuum Plasma Spray and the material's thermal characteristic under load is presented.

6170-39, Session 7

Thermomechanical characterization of high- temperature SMA actuators

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High Temperature Shape Memory Alloys (HTSMA) have been studied by numerous researchers. NiTi based ternary alloys with alloying elements like Palladium, Hafnium and Zirconium have shown promising results as high temperature actuators. Current practical applications of SMAs are restricted to temperatures below 100°C, approximately. Most high temperature SMAs investigated in the literature are limited to actuation temperatures below approximately 300°C. HTSMAs with actuation temperatures greater than 300°C can provide solutions to a whole range of high temperature applications in the automobile, aircraft and oil industries. It becomes a critical issue to address high temperature environmental effects on actuator performance and stable Shape Memory Effect (SME) response under such severe operating conditions.

The focus of this study is the thermomechanical characterization of HTSMAs at different load levels and various temperatures ranging from 300 - 500°C. Cyclic response and environmental effects are also studied. In order to investigate the above issues a NiTiPd HTSMA with a high composition of Palladium was used. The alloy was fabricated by vacuum arc melting technique, cast and hot rolled. Tension coupons and compression specimens were cut out from the rolled bar. A high temperature experimental setup was put together on a load frame to test the material at high temperatures under constrained actuation conditions. Certain key observations were made in the study of the NiTiPd high temperature shape memory alloy, including the material response in terms of actuation strains under certain specific applied stress levels and variable temperature profiles. The stability of the material response under cyclic actuation has also been investigated. The impact of exposure to environmental effects on the actuator performance has been finally studied and will be presented in detail.

6170-40, Session 7

Design of higher energy absorption materials based on shape memory alloy and composites

Y. Zhao, M. Taya, Univ. of Washington

Porous NiTi shape memory alloy with several porosities are processed by Spark Plasma Sintering (SPS). The compression behavior of the porous NiTi was examined with the aim of using it as a high energy absorbing material. A model for the macroscopic compression behavior of the porous NiTi is established. The analytical results are compared with the experimental data for porous NiTi, resulting in a reasonably good agreement. Based on the investigation of the porous NiTi and NiTi spring, an energy absorbing composite structure made of a concentric NiTi spring and a porous NiTi rod is processed. Both NiTi spring and porous NiTi rod are of superelastic grade. This composite structure exhibits not only high reversible force-displacement relation from small to intermediate loading but also high energy absorbing property when subjected to large compressive load. Therefore, it will be used repeatedly for low to intermediate impact loading and as a very high impact energy absorber for high impact loading. A model for the compressive force-displacement curve of the composite structure is presented. Compared with the experimental data, the predicted curve matched reasonably well. Higher porosity (25% - 40%) NiTi is processed by SPS. Two types of powder mixture are used, one is Ti, Ni and TiH2 (Type-1), the other is NiTi and TiH2 (Type-2). It is found that Type-2 exhibits more ductility and superelasticity.

6170-41, Session 7

The effect of severe plastic deformation on the recoverable phase transformation in high- temperature shape memory alloys

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NiTi alloys are the most important shape memory alloys due to their superior mechanical and functional properties, however their use is restricted below 100 °C. In order to extend their utility in high temperature applications, higher martensitic transformation temperatures than 100 °C, lower temperature hysteresis, and better cyclic reversibility are required. The transformation temperatures of NiTi alloys can be increased by the addition of Hf and Pd, however, these additions lead to the degradation of thermal cyclic response under stress due to the decrease in critical stress for slip. In this study, severe plastic deformation via equal channel angular extrusion (ECAE) was used to increase the critical stress for slip by grain refinement down to nanometer range and by designing specific textures in NiTi and NiTi(Pd,Hf) alloys. We will present methods of engineering microstructure and texture using ECAE and resulting thermomechanical response including temperature hysteresis and enhanced cyclic reversibility.

6170-42, Session 7

On the characterization of thin sheets of Nickel-Titanium using digital image correlation

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Shape memory alloys (SMAs) are a group of metallic alloys that are able to revert to a previously defined size or shape when deformed and then heated past a set transformation temperature. This "shape memory" behavior is due to a shear-dominated diffusion-less transition between crystalline phases of different symmetries. SMAs display other unusual mechanical properties that make them highly useful, including pseudoelasticity, high vibration damping, high yield stresses, and high power to weight ratios. In addition, the alloys are durable and corrosion resistant. Nickel-Titanium, commonly referred to as Nitinol, is a promising shape memory alloy used in a wide variety of applications, including advanced biocompatible and MEMS materials.

This paper presents an experimental investigation into the propagation of a martensitic phase boundary through thin sheets of austenitic Nitinol. The phase boundary is observed using Digital Image Correlation (DIC). DIC is a full-field optical correlation method used to measure strain on the surface of an object by optically tracking a speckle pattern on the sample surface. Correlation software is then used to translate discrete speckle motion to strain fields that directly relate to

phase boundary nucleation and propagation.

Quasi-static uniaxial tension tests were performed on dogbone specimens conforming to ASTM Standard E8-M. The phase boundary propagation was investigated in solid specimens cut in different orientations, as well as in specimens with a centered hole and a side notch. Martensitic propagation was also investigated in a side crack specimen during fracture. Strain in the specimens ranged from approximately zero to eight percent. In addition to full-field information at high strain levels, interesting martensitic behavior at lower strain levels, approximately one percent, was observed. At the end of testing, small amounts of residual strain due to plastic deformation were shown to be present. The finite element modeling program ABAQUS was used to analyze the localized strain in both low and high strain cases. This data was then compared with experimental results.

The martensitic transformation is well-defined in the DIC images, providing a clear qualitative representation of the transformation behavior, as well as quantitative information. Although other methods have been used to explore phase transition in shape memory alloys, DIC is unique in providing a quantitative estimate of the strain inside the area of martensitic transformation, as well as providing full field information.

6170-43, Session 7

Model for the magnetomechanical behavior of NiMnGa driven with collinear field and stress

X. Wang, M. J. Dapino, The Ohio State Univ.

Much interest has been given to the development and understanding of ferromagnetic shape memory alloys (FSMAs) in the nickel manganese gallium (NiMnGa) system. Compared with other smart materials, for example piezoceramics and magnetostrictive materials, NiMnGa has the advantage of achieving both high bandwidth and large strains in response to magnetic fields. Indeed, while piezoceramics and magnetostrictive materials have high response frequencies, they can produce only small strains, normally on the order of 0.001. On the other hand, shape memory alloys can produce strains in excess of 8% in tension, but show a small thermal or mechanical bandwidth due to the restriction of thermal conduction. In NiMnGa, large bidirectional strains up to a maximum 10% are produced by twin boundary motion as martensite variants rotate to align respectively parallel or perpendicular to applied magnetic fields or stresses.

The magnetic shape memory effect was first observed by Ullakko et al., who reported strains of nearly 0.2% in unstressed NiMnGa single crystals. Since then several models have been proposed by different groups to explain the strain mechanism based on twin variant reorientation. But the existing models do not predict reversible strains without applying an external force or magnetic field orthogonal to the applied field as a restoring force.

This is done in applications by driving the material with an electromagnet and perpendicular loading stage. From our tests, a reversible compressive strain of 0.41% was produced along the [001] crystal direction of a cylindrical Ni50Mn28:7Ga21:3 rod without the need for an externally applied restoring force. This result is significant not only in that the underlying behavior cannot be explained by existing models for martensitic variant reorientation, but also because it enables a new class of solenoid-based transducers that are more compact, lighter, energy efficient and broadband than their electromagnet counterpart. This paper presents a thermodynamic model which offers an explanation for the reversible strain measured in the absence of an externally applied restoring force as well as for the smaller magnitude of strain produced by this sample.

In order to effectively design and control solenoid-based NiMnGa transducers in applications, the mechanism that governs the generation of field-induced strains must be understood and modeled. In this paper, pinning sites in the martensite are hypothesized to provide an internal restoring force allowing for reversible strain. The pinning sites, which are point defects, dislocations, second phase materials, compositional gradients or residual stresses, are hypothesized to have varying energies. During the reorientation process, the field does not provide enough energy to overcome the energy barrier which comes from the pinning sites. The twin boundary displaces against the pinning sites and as it does work against the pining sites, energy is dissipated. When the field is removed, the anisotropy energy returns the magnetic moments to the easy c-axis of the crystal and the pinning energy provides a restoring mechanism for the twin boundary, returning the sample to its original length and magnetization7. This theory provides an addition to previous models and an explanation for the smaller magnitude of strain produced by the sample.

In previous work by Faidley et al. the pinning energy was incorporated by considering a simplified two variant system in which pinning sites are assumed to behave as mechanical springs. In this paper, the mathematical formulation of the proposed mechanism shares a common thermodynamic foundation with other existing free energy models for ferromagnetic shape memory alloys. A thermodynamics approach similar to that presented by Kiefer and Lagoudas9 and Faidley et al. is used here. However, a constant bias stress caused by the pinning sites is considered instead of a spring pinned to the boundary as in Faidley et al.. The resulting model is therefore two-dimensional as it must accommodate the externally applied stress and magnetic field, as well as an orthogonal internal bias stress - which is responsible for the reversibility of the strain. The model is formulated by considering the Zeeman, elastic and bias stress energy. Constitutive relations for the strain and the magnetization are derived by differentiation of the Gibbs energy with respect to stress and field, in combination with evolution equations for the two-variant system. In order to test the validity of this approach, the mathematical model is implemented numerically and the results compared with strain and magnetization data collected by Malla et al. using a solenoid transducer.

6170-44, Session 8

Application of a MSMA constitutive model in the analysis of magnetomechanical boundary value problems

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Magnetic shape memory alloys (MSMA) have recently drawn considerable research interest due to their ability to produce magnetic field-induced strains (MFIS) at least one order of magnitude higher than those of ordinary magnetostrictive or piezomagnetic materials. They have shown the promise of greater actuation bandwidth than conventional shape memory alloys (SMA), since their actuation frequency is not limited by relatively slow heat transfer. The magnetic field-induced strain response is nonlinear and hysteretic in nature and it is coupled to a nonlinear change in the magnetization of the material. Therefore MSMA are not only interesting materials for actuator and sensor design, but also candidates for new magnetic material applications such as transducers, or voltage generators.

In the design process of MSMA actuators, which have now become commercially available on a limited scale, it is inevitable that the intrinsic coupling between mechanical and magnetic effects in these materials be addressed. A reliable constitutive model for numerical analysis is needed as a tool in the development process to go beyond trial-and-error development techniques involving extensive experimental testing. The main focus of this paper is on the modeling of the MSMA constitutive response, the correlation with experiments and the application of the constitutive model to solving specific magnetomechanical boundary value problems. All three of these steps are aimed at improving the design process of MSMA actuators and other applications. This includes employing the constitutive model to increase the accuracy of the MSMA characterization experiments themselves, as they provide the data on which the design process is based.

The magnetic shape memory effect (MSME) is a result of the rearrangement, i.e. detwinning or re-orientation, of martensitic variants in MSMA under the influence of magnetic fields. The field-induced variant reorientation process is explained by the tendency of the ferromagnetic martensite to nucleate and grow those variants whose magnetic easy axes are favorably oriented with respect to the applied magnetic field. This crystallographic rearrangement causes the macroscopically observable MFIS. Simultaneously, the magnetic microstructure evolves to align the intrinsic magnetization with the magnetic field through the variant rearrangement process and the additional mechanisms of magnetic domain wall motion and the magnetization rotation. The magnetic field-induced shape change is therefore always accompanied by a nonlinear magnetization behavior of the material.

The phenomenological MSMA model presented here is based on a free energy function in which the stress and the magnetic field strength are the independent state variables. Loading history dependence of the constitutive behavior, caused by dissipative effects, is introduced into the model through the evolution of internal state variables. In this approach the model distinguishes itself from most of the constitutive models presented in the literature, which are based on the minimization of the free energy. The considered internal state variables are the variant volume fractions, the magnetic domain volume fractions and the magnetization rotation angles. These variables are motivated by the crystallographic and magnetic microstructure. The energy function is comprised of the elastic energy, the Zeeman energy, the magnetocrystalline anisotropy energy and an interaction term. From the free energy expression the constitutive equations for the dependent state variables, namely the elastic strain and the magnetization, are derived in a thermodynamically- consistent manner by following the Coleman-Noll procedure. A reori-

entation function, subject to Kuhn-Tucker loading conditions, governs the activation of the evolution of the variant volume fraction. The corresponding evolution of the MFIS is described by a reorientation strain tensor and appropriate strain hardening functions. A calibration scheme has been devised to identify model parameters from experimental data.

The paper briefly discusses experimental work, in which a newly developed magneto-thermo-mechanical test setup has been used to measure the MFIS in MSMA single crystals. To illustrate the applicability of the model, the calibration procedure is employed to deduce a set of model parameters from the obtained experimental data. The constitutive model equations are reduced to reflect the loading conditions for the considered experiment. The MFIS and magnetization response are then predicted for different stress levels. It is evident from a comparison with the experimental data that the model predictions capture stress-dependence, the nonlinearity and the hysteretic nature of the constitutive response as well as the so-called first cycle effect.

After the predictive capabilities of the constitutive model have been validated, the model is utilized in the analysis of specific magnetomechanical boundary value problems. It has been indicated that in this manner the modeling effort can be used to improve the MFIS experimental setup itself, as well as the interpretability of the measured data. The motivation for this application is given by the fact that in the experiments the magnetic field measurements are conducted by placing a high sensitivity Hall probe close to the MSMA single crystal specimen. Due to the demagnetization effect encountered in all ferromagnetic materials, however, the magnetic field inside the specimen is significantly reduced compared to the externally applied field which the probe registers. Furthermore, the presence of the specimen itself perturbs the otherwise homogeneous magnetic field around it, which leads to the question of appropriate probe placement. To correctly deduce the magnetic field strength acting on the material in the interior of the specimen from the probe data, tabularized demagnetization factors are usually employed. However, these lose their validity if the considered body is not homogeneously magnetized. This problem is addressed by using a finite element analysis, in which the magnetostatic problem is solved for the specific geometries of the considered experiment. The computation accounts for the nonlinear magnetic behavior of the MSMA single crystal by utilizing the magnetization response as predicted by the constitutive model for a given stress level. The obtained magnetic field strength and magnetization distributions are utilized to compute a volume averaged (magnetometric) demagnetization factor. The error made by the common assumption of a homogeneous magnetization of the specimen is computed.

The paper concludes with a discussion of the capabilities and limitations of the introduced constitutive model and its applicability in the actuator design process. Possible extensions of the presented work and future efforts are outlined.

6170-45, Session 8

Design of ferromagnetic shape memory alloy composites

M. Taya, Univ. of Washington

Ferromagnetic shape memory alloys (FSMA) are attracting a strong attention among actuator designers and materials scientists, as they are considered to provide a larger force and stroke at fast actuation speed. There are three mechanisms of actuation associated with FSMA, (1) phase change by magnetic field, (2) variant rearrangement mechanism in martensite phase under constant magnetic field and (3) hybrid mechanism under magnetic gradient field. The University of Washington (UW) group identified that the hybrid mechanism is best suited for compact actuators with higher force and stroke capability.

In this talk, I will discuss the fundamentals of the hybrid mechanism of FSMA. Although FSMA has been studied by many materials scientists in the world, its applications to compact actuators are still very limited. If the hybrid mechanism is utilized, one can expand the application area of FSMA. However, the cost of FSMA is still expensive. Thus, UW group proposed the concept of FSMA composites whose actuations can be easily realized under the hybrid mechanism. FSMA composites which are best suited for use in the design of compact actuators. The technical challenges facing us are, processing of FSMA composites, MEMS design, analytical modeling. As to the modeling, I would like to introduce the FSMA composite modeling based on the Eshelby type model and laminated composite theory. The modeling will provide an actuator designer with optimized microstructure of FSMA composite.

6170-46, Session 8

A homogenized strain model for Ni-Mn-Ga driven with collinear field and stress

L. E. Faidley, M. J. Dapino, G. N. Washington, The Ohio State Univ.

Ferromagnetic Shape Memory Alloys (FSMAs) in the Nickel-Manganese-Gallium system have been shown to exhibit large magnetically induced strains of up to 9.5% due to magnetically driven twin variant reorientation. In order for this strain to be reversible, however, an external restoring stress or magnetic field needs to be applied orthogonal to the field and hence the implementation of Ni-Mn-Ga in applications involves the use of electromagnets, which tend to be heavy, bulky and narrowband. In previous work at The Ohio State University a sample of Ni[50]Mn[28.7]Ga[21.3] has been shown to exhibit reversible compressive strains of -4200 micro-strain along its [001] direction when a magnetic field is applied along this same direction and no externally applied restoring force is present. This reversible strain is possible because of an internal stress field associated with pinning sites induced during manufacture of the crystal. This paper analyzes the switching between two variant orientations in the presence of magnetic fields (Zeeman energy) and pinning sites (pinning energy) through the formulation of a Gibbs energy functional for the crystal lattice. The minimization of the Gibbs free energy yields a strain kernel which represents the predicted behavior of an idealized 2-dimensional homogeneous single crystal with a single twin boundary and pinning site. While adequate, the kernel has limitations because it does not account for the following: (a) a Ni-Mn-Ga sample consists of a large number of twin variants and boundaries, (b) the strength of the pinning sites may vary throughout the material, and (c) the local and applied magnetic field will differ locally due to neighbor-to-neighbor interactions. These limiting factors are addressed in this paper by considering stochastic homogenization. In similar models for ferromagnetic materials the effects of polycrystallinity, material inhomogeneities, inclusions, textures, and variable interaction fields are incorporated by assuming that the local coercive field and interaction field are stochastically distributed with appropriate densities. In this paper, stochastic distributions are used on the interaction field and on the pinning site strength, yielding a phenomenological model for the bulk strain behavior of Ni[50]Mn[28.7]Ga[21.3]. The model quantifies both the hysteresis and saturation of the strain. Model results are quantitatively compared with experimental data for various fields and loads applied along the [001] direction of the sample.

6170-47, Session 8

A multiscale model of thin film magnetic shape memory alloy actuators

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This paper investigates the nano-macro transition in magnetic shape memory alloy(MSMA) thin films using a recently developed sharp phase front-based three-dimensional (3D) constitutive model outlined by Stoilov (JSMS 2005), and originally proposed in the 1D context by Stoilov and Bhattacharyya (Acta Mat 2002). The key ingredient in the model is the recognition of martensite variants as separate phases in a MSMA domain. Evolution of the interface between these phases is taken as an indicator of the process of reorientation in progress. A formulation of the Helmholtz free energy potential based on Ising model has been derived. The implications of the external magnetic field on the initiation of phase transformation are studied for various mechanical loading modes. Finally, the issue of nano-macro transition is examined in the context of stress-strain-magnetic field response of Ni2MnGa MSMA thin film actuators.

6170-48, Session 8

Sensing behavior of ferromagnetic shape memory alloy NiMnGa

N. N. Sarawate, M. J. Dapino, The Ohio State Univ.

Ferromagnetic shape memory alloys (FSMAs) produce large strains under external magnetic fields. FSMAs in the Ni-Mn-Ga system exhibit strains of up to 9.5 % under fields of 400 kA/m [1]. The strain results from the rotation of martensite twin

variants which can be driven by external magnetic fields and also by external stress. Due to field activation, the frequency response of Ni-Mn-Ga alloys can be higher than that of thermal activation in shape memory alloys [2]. The large strain and high bandwidth make these materials useful for actuator applications [3]. The existing work on Ni-Mn-Ga has been largely focused on the effect of magnetic field on strain [4-8]. A number of models have been developed to explain the reversible and irreversible strains observed for drive configurations with stress and field applied parallel as well as perpendicular to each other [9-11].

The effect of external mechanical input on the magnetic properties of Ni-Mn-Ga is termed the reverse effect and has seen only limited investigation. Mullner et al. [12] first reported the change in the flux density of Ni-Mn-Ga under external quasistatic loading at a constant field of 0.7 T (558 kA/m). Suorsa et al. [13] studied the ability of Ni-Mn-Ga to generate a voltage in response to a mechanical impulse. In another study, the shape of a Ni-Mn-Ga rod was monitored by observing the change in the inductance of a coil in an electromagnet [14].

This paper aims at investigating the reverse effect of mechanical input on FSMAs in a comprehensive manner by studying the effect of external quasistatic and dynamic straining on the flux density of Ni-Mn-Ga. The results presented here show the variation of stress and magnetic induction under external quasistatic strain for a wide range of transverse DC bias fields. A significant change is observed in the flux density upon application of external deformation, indicating that the material can have potential applications for position, velocity, acceleration, and force sensing, and power generation. Similar to piezoelectric and magnetostrictive materials, FSMAs can also be realized as a new class of multifunctional smart materials, with larger actuation strains, high frequency response, and high sensitivity to large-deformation, small-force motion.

The experimental setup consists of a custom built electromagnet made from laminated transformer steel, which can produce DC and low frequency AC fields of up to 750 kA/m, with variation of less than 2% around the area of the pole faces. The external uniaxial quasistatic strain is applied using an MTS machine with Instron controller. A 6 mm x 6 mm x 20 mm single crystal Ni-Mn-Ga sample is placed in the center gap of the electromagnet. The sample is first converted to field preferred variants by applying a high transverse field of 720 kA/m. The sample exhibits a free field induced strain of 5.8 %. Then the sample is compressed at a fixed displacement rate of 0.025 mm/sec, and unloaded at the same rate. The flux density inside the material is measured using a Walker Scientific MG-4D Gaussmeter with a transverse Hall probe placed in the gap between the magnet pole and the face of the sample. This method of measuring induction has been used previously [15]. We have confirmed the accuracy of the method using FEA analysis, as the small air gap ensures that the flux density inside the sample and that acting on the probe are equal. The compressive force is measured by a 200 lb load cell, and the displacement is measured by an LVDT. This process is repeated under varying magnitudes of externally applied transverse fields produced by the electromagnet. The externally applied field is obtained from the calibration curve of the electromagnet as a function of the measured current.

The stress and flux density are recorded as a function of applied compressive strain at various bias fields. The stress-strain plots show similar characteristics as those seen in literature [16]. The flux density or magnetic induction plots are of interest for sensing applications. The stress and induction plots show similar characteristics in terms of magnetic field induced pseudoelasticity.

The magnitude of change in the magnetic induction over the entire compressive range can be defined as sensitivity. The change in induction is found to increase initially and then decrease after reaching an optimum point with increasing bias fields. This behavior can be explained from the easy and hard magnetization curves for Ni-Mn-Ga. The easy axis magnetization curve has a steeper slope, as the curve tends to saturate at low fields, 120 kA/m in this case. The hard axis magnetization curve has a lower slope with higher saturation field, 640 kA/m. When the sample is compressed at a constant field, the induction value changes from the corresponding easy axis value to the corresponding hard axis value. Hence, the optimum range occurs when the two curves are at maximum distance from each other. A significant flux density change of 0.23 T is observed at a bias field of 173 kA/m. A linear model by Likhachev and Ullakko [9] relating magnetization to strain is found give satisfactory predictions at higher fields during compression. However, the model fails to account for the non-linearity at lower fields, and the hysteresis observed in the data. Further investigation into developing a quasi-static model explaining the dependence of induction on strain will be carried out based on the free energy approach.

This paper will also include dynamic testing and characterization where the sample will be utilized to measure dynamic properties such as acceleration and force. The setup will involve a shaker-spring type arrangement [17] to apply dynamic forces on the FSMA sample, along with the electromagnet to apply transverse fields. The tests will be done with different bias fields and pre-stresses, under a wide range of frequencies. The induction values recorded will be compared with the force recorded by a PCB dynamic force transducer. A dynamic model will be developed to predict the frequency response.

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6170-49, Session 8

Magnetic-field-induced-strain in NiMnGa under the effect of small amplitude stress waves

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It has been previously shown that the magnetic-field-induced-strain (MFIS) from ferromagnetic shape memory alloys (FSMAs) can be affected by a high-frequency acoustic wave. When the maximum field is near the threshold for MFIS (around 5 kOe, well below saturation), the acoustic-assisted effect is substantial. The MFIS increases almost an order of magnitude with increasing drive frequency [1]. Recent tests conducted for magnetic fields below the saturation fields for the material show new results. In these experiments, the effect of a small amplitude stress wave was tested over a broad range of frequencies for a constant magnetic field drive with an amplitude of ±9 kOe and frequency of 0.5 Hz. It was found that the behavior in this magnetic field region was considerably different than in the lower amplitude magnetic field region. Over the same range of frequencies for the stress waves, there was negligible change in MFIS at ±9 kOe

6170-50, Session 8

Magnetic field induced martensite reorientation and martensite to austenite phase transformation in NiMnGa: guidelines to increase the blocking stress

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Magnetic shape memory alloys (MSMAs) have attracted increasing interest due to their ability to display one order of magnitude higher magnetic field induced strain (MFIS) than magnetostrictive materials. MSMAs also provide couple of orders of magnitude faster dynamic response than conventional shape memory alloys. Nevertheless, their blocking stress is only around a few megapascals. Earlier research focused on methods to increase the MFIS levels by altering composition and structure. There are not many systematic investigations for the optimization of the blocking stress and MFIS. In previous studies, magnetic field was only utilized to induce martensite reorientation and results achieved in magnetoplasticity and magnetoelasticity. However, magnetoelasticity caused by the field induced phase transformation was not investigated comprehensively.

We conducted an extensive study on Ni2MnGa single crystals with 5M martensite structure. The controlled parameters were the levels and rates of magnetic field, applied stress, and temperature of the sample. As a separate investigation, the effect of temperature was examined relative to the characteristic temperatures on both field and stress induced reorientation and phase transformation. Some physical parameters such as relative saturation magnetization and magnetocrystalline anisotropy energy of austenite and martensite phases, twin boundary and phase front mobility were determined. We have investigated the blocking stress, magnetostress and field induced strain levels as well as the conditions to observe magnetic field induced phase transformation in a repeatable manner (i.e. under magnetic field cycling). Besides, we explicitly revealed the effect of the operating temperature with respect to the martensitic transformation temperature and Curie temperature on these physical parameters and resulting magneto-thermo-mechanical materials response.

Modifying some of these factors resulted in: 1) the maximum blocking stress and magnetostress of about 6 MPa for the magnetic field induced martensite reorientation mechanism that provided more than 50% increase in previously reported work outputs in NiMnGa alloys; 2) magnetic field induced martensite to austenite transformation as a new actuation mechanism; 3) utilizing this actuation mechanism, an increase in cyclic blocking stress to 22 MPa with about 1% strain (magnetoelasticity) and magnetoplasticity with 4% strain.

An empirical correlation is proposed to distinguish between the stress dependence of the critical magnetic fields for martensite reorientation and phase transformation. Another observation elucidated that the MFIS evolution is magnetic field rate dependent. This was verified by a rate dependent two-stage variant reorientation where the maximum MFIS magnitude increased as the field rate increased.

6170-51, Session 8

Time-dependent magnetic field induced strain and permeability of combined acoustic and magnetic actuation of Ni-Mn-Ga single crystals

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The effect of acoustic energy input from a piezoelectric actuator on the magnetic-field-induced strain (MFIS) of Ni-Mn-Ga ferromagnetic shape memory alloys (FSMAs) near the composition Ni2MnGa is observed to enhance the MFIS performance in FSMAs.[Ref#1] The threshold field required to induce twin boundary motion is reduced by this new technique by up to one kOe and the strain can be increased by an order of magnitude depending on the magnetic field. To understand better the effect of a piezoelectric actuator, the dependence of permeability of a Ni-Mn-Ga single crystal on applied magnetic field, Ho, and on supplementary acoustic energy is investigated.[Ref#2] Because the permeability depends on the orientation of the magnetic moments, permeability(Ho) is able to distinguish a) domain wall motion from b) reversible magnetization rotation or c) irreversible field induced twin boundary motion.

In this work, the permeability and MFIS are simultaneously measured in the long direction of the crystals (100-cut measuring 5 X 2 X 15 mm) as a function of a magnetic field applied along the same direction. Above a threshold field, twin boundary motion is activated such that the twin variants having their easy axes aligned along the field direction tend to grow. The negative MFIS is observed as the shorter 'c' axis is aligned along the field direction. The permeability drops significantly at the threshold field after the variant rearrangement due to the twin motion. The effect on the threshold field of acoustic energy input at varying frequency and amplitude on the threshold field is investigated. With an introduction of acoustic energy, the threshold field is decreased by almost 1 kOe for 30 Vp-p applied to the piezoelectric stack actuating at 7 kHz (10% duty cycle).

The time-dependent MFIS and permeability under a constant field are also studied. The evolution of MFIS and permeability induced by a static field is observed over a time interval of 90 minutes. Typically, the twin boundary motion occurs abruptly once the field is sufficient enough to overcome pinning sites. In this study, the field is set constantly at approximately 1 kOe below the threshold field (Hth) to observe time-dependent MFIS and permeability due to stress relaxation and thermal fluctuation. The time dependent part of the MFIS varies roughly as A[1-e^(-t/T)]. An application of acoustic energy reduces the characteristic time constant (T) and increases A. At 30 Vp-p and 7 kHz piezoelectric assist actuation, the twin motion occurs instantly right after the field is turned on at H = Hth - 1 kOe. The knowledge of the time-dependent MFIS and permeability is important in the design for dynamic actuation. It is possible that the dynamic MFIS may response better if the duration of the driving field cycles is similar to the characteristic time. Moreover, the piezoelectric assist actuation may also have optimal effect when its frequency matches with the characteristic time.

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6170-79, Poster Session

Electroelastic field concentrations and frequency properties of Rosen-type piezoelectric transformers

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In the power electronic industry, miniaturization of power supplies has been an important issue. Recently, the piezoelectric transformers have been widely applied to the backlight systems for liquid crystal display to reduce the height and size of the notebook computers, digital video cameras, etc. The piezoelectric transformers have several inherent advantages over electromagnetic transformers such as high power density, high efficiency, low cost, compact size, and no magnetic noise. In most of the applications in the field of piezoelectric transformers, piezoelectric ceramics are subjected to both high mechanical stresses and intense electric fields to obtain high voltage step-up. Prediction of the intensified electroelastic fields in the vicinity of an electrode tip or possibly a crack tip would most likely require detailed finite element calculations. A two or three dimensional finite element model of piezoelectric material systems with cracks [1, 2] or electrodes [3, 4] was developed, and numerical simulation results were shown to be in quantitative agreement with test data.

This study examines the effect of frequency on the voltage step-up and electroelastic field concentrations in Rosen-type piezoelectric transformers in a combined experimental and numerical investigation. The transformers are fabricated using a hard lead zirconate titanate (PZT) C-205. The transformer is 50 mm length, 2 mm thick and 13 mm wide. Experiments were performed to measure the electrical impedance and voltage gain at various frequencies. The finite element method was also used to solve the coupled electro-elastic boundary value problem. The impedance and voltage gain were calculated and a comparison was

made between experiment and simulation. The effects of load resistance and capacitance on the electroelastic field concentrations were also discussed.

The calculated impedance minimum peak corresponds to the measured resonance frequency. Numerical predictions of the output voltage are also agreement with the measured values. The output voltage increases with the increase of load resistance.

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6170-80, Poster Session

Analytical model for performance prediction of unimorph piezoelectric composite actuators

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In most applications of unimorph piezoelectric actuators, the simply supported boundary condition is frequently used to give the highest value of actuating force and transverse deflection. In this study, we derive the analytical solutions for the simply supported and multilayered unimorph piezoelectric composite actuator as a beam model under applied voltage and external mechanical loads. The obtained solutions based on Rayleigh-Ritz technique including thermal effect and fully piezo-mechanical coupling effect show their convenience in various problems with different loading conditions. Due to the analytical nature, these solutions can also be served as benchmark to check various composite beam theories and numerical methods used for modeling of layered composite beams of different thickness with the shear deformation effect included. The von-Kármán nonlinear terms in strain-displacement relations and the material nonlinearity of PZT wafer are also taken into account in the model. The nonlinearity appears as an important factor in predicting performance of this actuator type. As a numerical illustration, full models (with tabs) of existing series and new generations of LIPCA (LIghtweight Piezo-Composite Actuator), LIPCA-C3, single-crystal ceramic mini-LIPCA are analyzed. The predictions are verified by finite element analysis and experiment results. Limitations of the approach are figured out in this study and suggestions for future research activities on buckling, vibration and dynamics problems for full model of actuators including tabs are also discussed.

6170-81, Poster Session

Development of a nonlinear piezoelectric finite element code

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Application of piezoelectric materials in sensors and actuators are leading to fast development of smart structures technology in many areas such as aeronautics, robotics and MEMS. In the piezoelectric structures, polarization switching may occur due to non-uniform fields and field concentration. Numerical analysis and design tools for piezoelectric structures are needed for the analysis of these structures as well as for the research and development of new electromechanical coupling materials. We report the development of a piezoelectric finite element code that is implemented with a nonlinear piezoelectric model. The nonlinear material model takes field induced polarization switching into consideration, the finite element code therefore can provide nonlinear analysis and give more accurate results for structures where field concentration and polarization switching may occur. In the finite element formulation, the displacement and the electric potential serve as independent variables. A thermodynamics based macroscopic constitutive model for nonlinear piezoelectric materials is implemented into the coupled-field finite element code. The developed finite element code is verified and a piezoelectric structure is analyzed using the code with the results compared with the linear solution.

6170-82, Poster Session

Dynamic performance of a magnetorheological fluid squeeze film damper under AC excitation

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Based on the special properties of the Electrorheological(ER)/ Magnetorheological(MR) fluid, a series of controllable vibration-damping devices or actuators have been developed and shown that the effectiveness and the controllability of the ER/MR fluid based vibration-damping devices to isolate and control the vibration. Most previous investigations have focused on the dynamic behaviour of ER/MR fluid vibration-damping devices under a static electric/magnetic field, the behaviour of these vibration-damping devices under an alternating electric/magnetic field has not been thoroughly investigated, limited papers are on the ER fluid vibration-damping devices, few papers on the MR fluid vibration-damping devices.

In this paper, the dynamic performance and the capability of the MR fluid squeeze film damper for attenuating rotor vibration under an AC sinusoidal magnetic field is experimentally studied on a flexible rotor. It is shown that as the frequency of AC sinusoidal magnetic field increases, the capability of the MR fluid squeeze film damper to attenuate rotor vibration significantly reduces. There are a maximum frequency of AC sinusoidal magnetic field for a given magnetic field strength to realize the MR effect and a minimum strength of AC sinusoidal magnetic field for a given frequency of AC sinusoidal magnetic field. When the frequency of AC sinusoidal magnetic field is over the maximum frequency or the strength of applied AC sinusoidal magnetic field is less than the minimum strength of AC sinusoidal magnetic field, the MR activity almost completely disappears and the dynamic behaviour of the MR squeeze film fluid dampers under a high frequency AC magnetic field is the same as that without magnetic field. In the rotor vibration control of view, it is not necessary to use the AC sinusoidal power supply for the MR fluid squeeze film dampers.

6170-83, Poster Session

Characteristics of TiNi shape memory alloy processed by vacuum plasma spray

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TiNi alloys are the most popular shape memory alloy that exhibit excellent shape memory SME) and superelastisity (SE) effects. Therefore, the TiNi alloy is utilized in many fields. One disadvantage of TiNi alloys are, however, the difficulty of cold and hot working and machining these alloys, because the TiNi alloy exhibits high work hardening rate. Therefore, shaping of the TiNi has been restricted to simple shapes; plate, rod and wire. In addition, the machining of TiNi to final shape is costly. To overcome these problems, a spray forming process using vacuum plasma spray (VPS) processing was proposed. VPS can form thick TiNi deposits onto three-dimensional surfaces by spraying TiNi with a plasma jet to form 3D shape, into near-net shapes.

TiNi specimens were formed with a VPS process with the aim of achieving high density TiNi specimens made from TiNi powder. The VPS deposited specimens were machined to cylindrical shape with diameter of 5 mm and length of 9 mm. After the machining, the specimens were subjected to various heat treatments. As- homogenized and aged specimens were subjected to x-ray diffraction (XRD) analysis to obtain its microstructure and also to differential scanning calorimetry (DSC) to obtain its transformation temperatures (Ms, Mf, As and Af).

Compression testing was conducted at different testing temperatures to obtain

characteristic stress-strain (SS) curves. The SS curves conducted at different temperatures exhibited both SME and SE behavior. The values of recoverable strain of VPS deposited TiNi alloy exhibited SME and SE comparable to those of bulk (cast & wrought) TiNi reported by other researchers. Therefore, it has been concluded that VPS forming may be a viable processing near net shape forming route for economically producing TiNi into larger and more complex components.

6170-84, Poster Session

Shape memory films surface study by ellipsometry methods

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Adaptive materials integrate actuating and sensing materials into a structural material. The development of polymer composites with embedded shape memory alloys can open new perspectives with respect to the development of engineering structures with adaptive shape, stiffness, damping and other properties. The development of these advanced composites with embedded shape memory alloy wires is still in an embryonic stage. Given ellipsometry measurements with variable angle and directions of light incidence in wide spectral range of optical properties copper based alloy which require further research before these adaptive composites can be used in industrial applications.

6170-85, Poster Session

Modification of the properties of Ni-Mn-Ga

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The alloys were prepared by arc melting followed by directional solidification. Subsequently the alloys were homogenized at 800°C within 96 hours, quenched in ice water and tempered at 500°C within 3 hours. The cylindrical samples were prepared by spark-cutting.

The SEM and EDS studies were done using Hitachi S-3500N microscope. The TEM observations were performed in JEOL JEM 1200 EX microscope. Samples for the TEM were electro-polished at -20°C.

To determine the phase transitions and Curie temperatures the measurements with the use of DSC Q 1000, with heating/cooling rate of 10K/min, were performed. The x-ray diffraction analyses on bulk specimens were done using Philips PW 1830 diffractometer, Cu Kα. The HV was measured using FV-300 device with 98.07N load.

The FSME measurements were carried out on a self-built device MSM-1. The specimens had 3 mm diameter and 4 mm length. The magnetic field direction was perpendicular to the long axis of the sample.

Microstructure of the alloys studied strongly depends on the Tb content. The grain size drops from 200-400μm for the Tb-free sample down to 30-50μm for the sample having 2.03 at.% Tb. This is a significant change which affects the mechanical properties.

It was also found that the terbium does not go into solution with the matrix Ni2MnGa phase. It is evident from the EDS data that the terbium exists in the grain boundaries. Some larger precipitates of Tb in the grain boundary area are also visible. The mean composition of the boundary layer is: Tb - 16, Ni - 55, Mn - 7 and Ga - 22 at.%. It was found that terbium not only affects the grain size, but also changes the morphology. For the low Tb contents the grains are elongated parallel to the solidification direction. This elongation becomes perpendicular to this direction for the higher Tb contents.

6170-86, Poster Session

Shear mode acoustic actuation of Ni-Mn-Ga single crystals

J. M. Simon, S. R. Hall, D. C. Bono, Massachusetts Institute of Technology

The acoustic actuation of Ni-Mn-Ga ferromagnetic shape memory alloy (FSMA) single crystals by the propagation of shear waves is investigated. Previous experiments have utilized compressive or tensile longitudinal stress waves generated by piezoelectric stack actuators and propagating along the length of 100-cut crystals to initiate twin boundary motion. In shear mode actuation, a rectangular prism is cut from the single crystal such that its longest dimension is parallel to the twin plane normal. The wave is generated either by one of two d33-type piezoelectric stack actuators mounted at 45° to the length of the crystal, or by a single d15-type shear actuator mounted to its base.

Bi-directional actuation is demonstrated, corresponding to a shear strain of approximately 6% that is consistent with the measured c/a ratio of 0.94. For a crystal 5 mm in length this is equivalent to a displacement of 0.6 mm, achieved in fewer than 200 pulses. A single pulse at the maximum piezoelectric peak voltage can lead to a displacement of over 2 ?m, while with lower-voltage pulses displacements in the sub-micron range can be achieved.

Results using both the double-stack and shear actuator configurations are discussed. The effects on actuator performance of the composition, dimensions and thermal and mechanical histories of the Ni-Mn-Ga single crystal are also examined. The selection of reflecting and attenuating materials and the input pulse shape and frequency are optimized. The actuator is tested both while unloaded and against various loads. Potential applications as either a push-pull actuator or a micropositioning device (e.g. optical switch) are explored.

6170-87, Poster Session

Synthesis, characterisation and applications of Mn-Zn ferrite nanoparticles

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Abstract

This paper deals with the synthesis, characterization, and some applications of Mn-Zn ferrite nanoparticles. The Mn-Zn ferrite was prepared from metallic nitrates, iron citrate and citric acid with the co-precipitation method with different pH values and it was further used to synthesis Mn-Zn ferrite with polariser i.e. H2O2 (Hydrogen peroxide).The X-ray diffraction pattern shows the single phase spinel structure of the ferrites. The effect of pH and the oxidizing agent on the electrical properties of Mn-Zn ferrite was studied. The d.c. resistivity is improved with the pH value and further improved by the addition of H2O2 (Hydrogen peroxide), which acts as a strong oxidizing agent. The dielectric constant decreases with increasing pH value; at the same time the dielectric loss also decreases. Further the decrease in dielectric properties by addition of oxidizing agent are justified by inverse proportionality between resistivity and dielectric constant.

6170-52, Session 9

Modeling symmetric magnetoelectric laminates

G. P. Carman, Univ. of California/Los Angeles

This presentation describes analytical models for symmetric magnetoelectric laminates composites. This modeling effort consists of both 1-D and 2-D laminates that are symmetrically oriented (i.e., absence of bending). Using the appropriate constitutive relations, boundary conditions, governing equations, the effective properties of the layered materials were developed. During this study, we determined that representative geometries could be defined to model all plausible layups. A wide range of studies was conducted, varying the material properties and the volume fraction of each configuration. Results show that maximum values of the magnetoelectric coefficient are obtained at specific volume fractions, which is a function of the material properties and layup, and thus will vary from laminate to laminate. In addition to maximizing the magnetoelectric coefficient, we discovered that a 1-D layup surpassed the 2-D laminates by a factor of five for several specific configurations. Several magnetoelectric laminates were manufactured and results show reasonable correlation with the analytical data.

6170-53, Session 9

Magnetoelectric properties in NCF/PZT bulk laminate composites

S. V. Suryanarayana, B. S. T., N. B. S., Osmania Univ. (India)

Magnetoelectric (ME) effect is observed in two- phase composites consisting of Piezoelectric and Piezomagnetic materials, under the action of an external magnetic field, which is absent in either of the phases. In the present work, the bulk laminates of Ni-Co-Mn ferrite (NCF) and Lead Zirconate Titanate (PZT) were prepared. The geometry of the samples is NCF-PZT-NCF. Thickness of NCF and PZT were varied between 0.5 - 1mm and 0.3 - 1mm respectively. Magnetoelectric (ME) measurements was carried out on these laminates using the Dynamic method. The ME output as a function of thickness ratio, dc and ac magnetic field was

studied. It was observed that the ME output increases with increasing thickness ratio. The highest ME output of 3.53 V/cm was found to observed at a fixed AC magnetic field of 64 Oe (1.008 KHz AC frequency) for the sample with thickness a of NCF 1mm and a thickness of PZT 0.3mm when a DC bias field of 0.75kOe.This value higher than bilayers of lanthanum manganates-PZT (0.03V/cm), NFO-PZT (0.2V/cm) and comparable to Terfenol-D-PZT (4.68V/cm). The Magnetoelectric coefficient (✔✉ was calculated for the samples.

6170-54, Session 9

Ferroelectromagnetic studies on BLSF compounds

S. V. Suryanarayana, B. S. T., V. Ramana, Osmania Univ. (India)

Ferroelectromagnetics belong to the class of compounds that complement ferroelectric or ferromagnetic materials and display simultaneous electric and magnetic ordering. As a result, these materials exhibit change in polarization by the application of magnetic field, a change in magnetization on the application of electric field and often some coupling between the two giving rise to an effect called magnetoelectric (ME) effect. The coupled electric and magnetic ordering in ferroelectromagnetics is accompanied by the formation of domains and domain walls. SrBi5-xLaxTi4FeO18 ceramics belongs to the Bi4Ti3O12 + n BiFeO3 family of compounds, which exhibits ferroelectricity and magnetism and hence the ME effect. Present study describes the ferroelectromagnetic studies on 5-layered SrBi5-xLaxTi4FeO18 (x=0 to 1) ceramics. Ferroelectricity of these ceramic samples is determined by observing the Curie temperature by the dielectric studies. Static pyroelectric method is employed to determine a peak in pyroelectric current, which corresponds to the ferroelectric transition temperature. ME output obtained in the present system is 640mV/cm, which is the maximum in any single phase bulk compounds. The results are presented as a function of composition and a comparison is made on the ME outputs obtained in the case of other single-phase bulk ceramics. The system offers itself as a candidate material for the observation of multifunctional physical properties that can be exploited for sensors and actuators.

6170-55, Session 10

A comparative study on macrofiber composites and active fiber composites with metal-core piezoelectric actuators/ sensors

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Piezoelectric sensors and actuators have gained considerable interest by investigators and researchers for the use in intelligent/smart structures and micromechanical systems. Furthermore, demand from industry for sensors and actuators with higher quality and better performance for special applications has lead the researchers to design piezoelectric systems with optimal configurations to enhance the performance of such actuators and sensors. Finite Element Method (FEM), as an alternative technique for stress and strain analysis of the micromechanical and electromechanical systems and structures, has been employed to numerically investigate the performance of the Metal-Core Piezoelectric Fibers (MPF) as an Active Fiber Composites (AFC) and Macro Fiber Composites (MFC). The individual constituents are modeled with their corresponding properties and Finite Element Analysis (FEA) is performed to study the free expansion of the piezoelectric actuators and then the results are compared with the experimental data provided by the manufacturers to verify the finite element models. Next, the generated three-dimensional models of the MFC and MPF/AFC were separately embedded in a composite structure to investigate their constrained extensions. Finally, the results are compared and the performance of each actuator is discussed in details.

6170-56, Session 10

Reliability of integrated active fiber composites in quasi-static cyclic and fatigue environments

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Active Fiber Composite (AFC) materials composed of interdigitated electrode (IDE) screen printed on Kapton film and piezoelectric Lead-Zirconate-Titanate (PZT) fibers in an epoxy matrix have become very popular in recent years in smart materials research. Due to a thin profile, flexibility and actuation performance, AFC elements can be used as the actuator or sensor component in composite laminate smart material systems such as active rotor blade applications. The design and implementation of smart materials in aerospace applications requires a clear understanding of the strain limits and fatigue reliability of the system. Currently though, the question of AFC reliability has not been widely explored in different strain and fatigue environments.

AFC reliability and performance in quasi-static strain and fatigue environments is addressed in the current study. AFC elements were integrated into two types of composite laminates, and then subjected to cyclic tensile tests. The strain sensing property of AFC was used to gage the performance and health of AFC during testing. Due to the electro-mechanical coupling nature of the PZT fibers, AFC sensor performance can be used as a strong indicator of actuation performance given similar loading conditions. Woven glass (GFRP) and uni-directional carbon (CFRP) fiber reinforced plastic laminates were used for the laminate material. AFC were integrated into the GFRP laminate via cutout insertion and in the CRFP specimens, AFC were integrated via cutout insertion and interlaced methods to gage the effect of integration technique on AFC reliability.

Monotonic cyclic tensile testing was performed on both the CFRP and GFRP integrated specimens to assess AFC reliability at increasing strain levels in the different material environments. The AFC voltage output signal was monitored during testing to examine the subsequent trend in AFC sensitivity in relation to applied strain. In addition, acoustic emission (AE) monitoring was used during cyclic testing to track damage evolution in the AFC elements and in the host laminates. Fatigue testing was performed on AFC integrated in GFRP laminates at low strains (below 0.15%) to gage the ferroelastic reliability of AFC over millions of cycles.

Quasi-static strain experiments showed AFC performance to be stable below strains of 0.15%, and showed degradation between strains of 0.20% to 0.50%. AE monitoring revealed damage initiation in the AFC area of the laminates at and above strains of 0.15%. The increase in AE activity and AE intensity corresponded with a drop in AFC performance as seen by a decrease in the sensitivity of the voltage output signal. Following cyclic testing, optical microscopy of polished sections of integrated AFC specimens revealed that crack formation in the PZT fibers occurred at the IDE finger edges. The location of cracks in the PZT fibers is attributed to the polarization character inherent in IDE based piezoelectric elements.

6170-57, Session 10

Overview on macrofiber composite applications

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The present paper is giving an update on availability and system developments of piezo fiber composites based on the MFC technology. The Macro Fiber Composite (MFC) is manufactured by Smart Material Corp. on a full-scale production basis. Recently, two new devices have been added to the MFC family: A contracting MFC with the advantage of reducing the driving voltage to 360V and a high temperature MFC for operation temperatures up to 180 °C.

Research and development of piezo fiber composites is still ongoing on different levels, like constitutive phases (piezoceramic, epoxy, insulating and conductive materials), scale, shape and connectivity, electrical and mechanical field distributions, interfaces and geometry, coupling to the load carrying structures (size scaling, placement), the electronics (voltage, current, time) and reliability issues. Knowledge on all of these levels is necessary to improve device performance and the efficiency for smart structure applications.

When embedded or attached to flexible structures, these actuators provide distributed solid-state deflection and vibration control. Commercial applications are still under development and are seen in vibrational and noise reduction, shape control, micro positioning, strain measurement and structural health monitoring.

The correlation between structure and the design and placement of the actuators has also been analyzed showing a strong interaction. E.g., piezo composite actuators or sensors and structures must be designed in close combination.

Because basic performance parameters are considerably improved, like for example energy economy, precision and comfort, a widespread use is expected in the very near future. The presentation will highlight the latest commercial applications for the MFC technology.

6170-58, Session 10

Improvement of actuation displacement and force of LIPCA implementing bifurcation phenomena

Q. V. Nguyen, H. C. Park, K. J. Yoon, N. S. Goo, Konkuk Univ. (South Korea)

In currently actual applications, LIPCA (LIghtweight Piezoceramic Composite Actuator) only can produce a few millimeters even though it is operated at its natural frequency. The actuator has been used for flapping devices, and the flapping performance is degraded quite quickly when the weight of wings becomes slightly heavy. For this reason, the actuation displacement and force of LIPCA need to be improved when LIPCA is used in a flapping device as an actuator. When the LIPCA is under compressive load up to slightly lower than its bifurcation load, the LIPCA may buckle if a proper electric field is prescribed. Therefore, the bifurcation can make the LIPCA create larger actuation displacement and force at the same time. To predict and search for a proper combination of the compressive load and the electric field for this purpose, the actuation displacements of LIPCA are calculated by the geometrically nonlinear finite element analyses based on the thermal analogy technique. The geometrically nonlinear analysis is used in the analysis because the LIPCA has the initial curvature due to the curing process, which plays a role like the initial geometric imperfection. In the finite element modeling, the three dimensional model including two tabs of LIPCA for laminated composite plate with piezoceramic material layer, glass/epoxy composite and carbon fiber composite layers is used. By varying the applied compressive load and electric field, the displacement changes at central point of LIPCA are examined to figure out the proper combination of the compressive load and electric field. The calculated actuation displacements from the geometrically nonlinear analysis are larger than those from the linear analysis. We could find a proper combination for the compressive load and electric field from the proposed analysis. Therefore, it is feasible to apply those results for improving and developing the flapping devices and the other purposes. The strength of LIPCA is also estimated and examined, to make sure that the LIPCA including piezoceramic layer can be operated in safe condition. The experiments have been carried out to verify and validate those results.

6170-59, Session 10

Hysteresis characterization using charge feedback control for Lipca actuators

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Pre-stressed composite piezoelectric actuators have become attractive for a wide variety of aerospace and industrial applications, for example the positioning of optics and in flow control. This study focuses on characterization of a Lipca series composite piezoelectric actuator subjected to charge-feedback control. The design and implementation of a charge feedback control circuitry is discussed, as well as implications for precise control of such actuators. In contrast to the voltage-control mode, charge-feedback control exhibits significantly less displacement hysteresis, and characterization is of importance for the continued development of applications involving composite piezoelectric actuators.

6170-60, Session 11

Characterization of piezoelectric effect and mechanical properties of cellulose-based electro-active paper actuator

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Recently, cellulose based paper has been reported to have active properties such as piezoelectric effects and ion migration effects. It is reported that cellulose based Electro-Active Paper (EAPap) actuator has some advantages compared to widely used electronic EAP or Ionic EAP actuators due to its merits in terms of lightweight, dry condition, large displacement output, low actuation voltage and low power consumption. A promising EAPap actuator has been developed using cellulose paper. Several researches for EAPap actuators have been conducted to investigate the performance, sensitivity, power consumption, environmental effects such as temperature and humidity. However, the actuating mechanism is not quite well known until now on.

In this paper, material characteristics and piezoelectric effects of cellulose based EAPap actuators will be investigated and piezoelectric actuating mechanism of EAPap actuator will be studied. Although humidity is a dominant factor and ion migration effects are considered as dominant actuating mechanism of EAPap actuator, cellulose is quite well known to have dominant shear piezoelectric effect. This can provide the clue of the piezoelectric actuating mechanism of EAPap actuator. Therefore, anisotropic material properties of EAPap actuator will be characterized first and shear piezoelectric constants be measured to show the piezoelectricity of EAPap actuator. After that, shear piezoelectric actuating mechanism will be modeled for EAPap actuator. It is expected that the shear piezoelectricity of cellulose paper can provide the potential of wide application of EAPap actuator.

6170-61, Session 11

Development and characterization of carbon nanopaper-based nanocomposite materials

J. Gou, S. O'Briant, Univ. of South Alabama; B. Fan, G. Song, Univ. of Houston

This research explored a new concept to fabricate nanocomposite materials based on carbon nanopapers, which function as both structural reinforcements and sensors in composite structures. In this method, carbon nanotubes/carbon nanofibers were preformed as nanopaper by multi-step dispersion and micro-filtration of the suspension of carbon nanotubes/carbon nanofibers. The strips of carbon nanopapers were then integrated into composite structures by using Resin Vacuum-Assisted Resin Transfer Molding (VARTM) process. The microstructures of the composites were characterized with SEM and AFM. The mechanical properties of the composites were studied with tensile test and dynamic mechanical analysis. The experimental results show that the integration of the strips of carbon nanopaper into composite structures enhanced the mechanical properties of composite structures in terms of strength, stiffness, damping, and toughness. In addition, the strips of nanopaper embedded into composite structures were used for strain sensing and crack monitoring.

6170-62, Session 11

Electric field-alignment of high-aspect ratio inclusions in polymers

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This paper focuses on developing multifunctional polymer composites by aligning micro and nano inclusions in photocurable polymers. The ultimate goal is to tailor the physical properties of the composites by controlling the degree of alignment of the inclusions. By processing and comparing random and field-tailored polymer nanocomposites, we plan to quantify the relationship between processing parameters and morphology in a range of polymer nanocomposites, and to develop a theoretical understanding that relates the microstructure to the charge transport properties.

Glass fibers and carbon nanotubes (CNTs) are dispersed in a polymer liquid. The polymer matrix is an epoxy. Both ac and dc electric fields are used. The aligned inclusions are then immobilized in the epoxy by photopolymerization, with the electric field still on. The alignment of the inclusions is investigated as a function of magnitude, frequency, and duration of the applied electric field. Evidence of alignment is evaluated using optical microscopy and SEM, dynamic mechanical analysis (DMA) and dielectric spectroscopy. Degree of alignment is assessed using polarized Raman spectroscopy. The storage modulus is measured to study the effect of aligned inclusions on the structural reinforcement of the composite. Percolation threshold is investigated by measuring static electrical conductivity and dielectric constant parallel and perpendicular to the aligned composites. Effect of alignment on the percolation distribution is studied. A CNT-polymer composite configuration where the material is conductive in the planar direction whereas it is insulating in the out-of-plane direction is achieved. Ordering of inclusion network may allow dual sensing and actuation, through control of the percolation threshold. Sensing comes from change in electrical conductivity as percolation network is disturbed by stress/strain. Actuation comes from electromechanical coupling arising from interaction between CNT and the polymer chains.

6170-63, Session 11

Magnetoelectroelastic coupling solution for a penny-shaped crack

B. Wang, The Univ. of Sydney (Australia)

Electro-magneto-mechanical coupling effects have been observed in single-phase materials and two-phase composite materials. Due to multi-field-coupling effects, a magnetic field may induce an electric field and an elastic field in magnetoelectroelastic materials, and visa versa. The coupled properties of magnetoelectroelastic materials offer great opportunities for engineers to create

so-called smart materials/intelligent structures that are cable of responding to internal and/or environment changes. Most magnetoelectroelastic materials are brittle. Defects are often unavoidable in these materials. Work has been directed towards the crack tip field intensity factors. For the reliability evaluation for the magnetoelectroelastic materials, it is necessary to know the expressions for the crack tip coupled magneto-electro-elastic fields. This paper solves the penny-shaped crack configuration in transversely isotropic solids with coupled magneto-electro-elastic properties. The crack plane is coincident with the plane of symmetry such that the resulting elastic, electric and magnetic fields are axially symmetric. The mechanical, electrical and magnetical loads are considered separately. Closed-form expressions for the stresses, electric displacements, and magnetic inductions near the crack frontier are given.

6170-64, Session 11

Ultrafast optical dynamics in VO2

S. I. Lysenko, V. S. Vikhnin, G. Zhang, A. Rua, F. E. Fernandez, H. Liu, Univ. de Puerto Rico Mayagüez

Design and development of light-controlled solid-state optical switchers, storage devices, infrared laser cavity mirrors based on metal-oxide films is upcoming branch of modern optoelectronic technology. In this work the laser induced insulator-to-metal (I-M) phase transition in VO2 thin films was explored by femtosecond optical pump-probe spectroscopy. The 400 nm wavelength pump beam provides sufficient energy for interband transition in VO2 between occupied lower 3d level and π^* band hybridized with upper 3d one. Optical pumping of free carriers in VO2 initiates extremely fast changes in transmittance and reflectivity, which behavior is strongly dependent on excitation pulse energy and structural properties of the sample.The 130 femtosecond laser pulses were applied for measurements of transient reflection and relaxation processes, and to characterize the carrier dynamics during I-M transition in 10E-13÷10E-9 temporal-scale.

Transient optical reflection was measured as a function of pump pulse energy and time delay between pump and probe pulses. The dynamic of photoexcited electrons and phonon relaxation process were studied using an optical delay line which can precisely change the timing between pump and probe pulses. Analysis of relaxation times of VO2 system during phase transition allows suggesting the formation of an intermediate state by pure electronic mechanism without complete lattice relaxation from monoclinic to tetragonal structure.

To analyze the ultrafast change of spectral properties of the VO2 sample the ultrashort white light pulses were used as a probe. White light continuum was generated by focusing of 800 nm femtosecond pulses on the sapphire plate and then focused on the sample. The reflected light was delivered into spectrophotometer. The spectral records in optical region are conducted at different fixed time delays between pump and probe pulses as well as at different temperatures of the sample. Comparison of the VO2 transient reflectivity for both VO2 temperatures corresponded to insulator and metallic phases gave information about light induced ultrafast structural transformation of VO2. The experimental data shows that the complete lattice transformation can be observed at the 10E-12 temporal-scale for ≤50 nm thick film as depended on optical pump pulse energy.

The excitonic model is suggested for light-induced insulator-metal phase transformation. The tunnel transition is caused by photoinduced Frenkel and clusterized Wannier-Mott vibronic excitons. It is expected that the specific intermediate states are related to vibronic Wannier-Mott excitons cooperated in clusters.

Upon a laser illumination an ultrafast (in ~10E-13 sec) change in reflectivity and its following pump-dependent relaxation process (in ~10E-9 sec) are observed for VO2 at different temperatures, in insulator and metallic VO2 phases. The study of transient reflectivity for VO2 in metallic state has allowed proposing the model for excited state dynamics at temperatures above insulator-metal phase transition.

6170-65, Session 11

Nonlinear optical characterization of glass-embedded silver nanoparticles

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The metal-dielectric nanocomposite systems are the object of increasing interest in modern optoelectronics due to its promising applications in ultrafast functional electronic, optical switching, and optoelectronic devices. The physical properties of small silver particles, including their optical properties are strongly dependent on external high-intense electromagnetic excitations as well as on local structural and geometric parameters of particles caused by the preparation process. Silver nanoparticles (NP) embedded in aluminophosphate glass were prepared by melt and heat treatment processes. A red shift of the surface plasmon resonance (SPR) peak is observed as particle size increases, with the quadrupolar plasmon excitation being prominent for the more intensely heat treated samples. Low-temperature photoluminescence studies of Ag NPs embedded in the glass matrix show a broad band emission at ~410 nm with a dip which has a minimum at wavelength corresponded to dipole SPR mode in spherical Ag NP. Such a dip is assigned to reabsorption of Ag2O emission by NPs. The nonequilibrium carrier dynamics in Ag nanoparticles was explored by ultrafast optical pump-probe spectroscopy. The time-resolved reflectivity measurements have shown the particle size-dependent nonlinear optical dynamics on a picosecond and nanosecond time scale. The relaxation mechanism of the electron-phonon system will be discussed. Laser-induced nonlinear optical response of NP was observed in transient reflection and degenerate-four-wave-mixing measurements. The third-order susceptibility is observed in a nonlinear holographic experiment. The ultrafast relaxation dynamics of electron-phonon coupling on the 10E-13÷10E-11 sec temporal-scale shows size- and pump power-dependent properties. Dependencies of electron-phonon coupling rate and coherent acoustic oscillations on NP size will be discussed in terms of a two-temperature model and stress generation by optical absorption. Kinetics study suggests that the nonequlibrium optical excitation of the NP ensemble leads to coherent acoustic oscillations of NP with different eigenfrequencies in the nanocomposite. Complete relaxation of nanocomposite materials occurs on a ~10E-9 sec time scale and can be assigned to phonon system thermalization.

6170-66, Session 11

Electric reaction arising in bone subjected to mechanical loadings

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Bone is smart material self-accommodating its shape according to condition of surroundings. On the other hand, it has been known that electrical potential generates from bone by mechanical stimulation. This is piezoelectricity of bone. The aim of present study is the investigation of the proper piezoelectricity arising in bone. Firstly, specimen was fabricated from femur of cow, and material properties such as bone density were measured by laser ultra sonic technique. Secondary, 4-point bending test was conducted up to fracture, and electric reaction arising in bone was measured during loading. Thirdly, cyclic 4-point bending tests were conducted to investigate the proper piezoelectricity arising in bone. It is important to investigate electrical reaction arising in bone when bone is given mechanical stimulation because piezoelectricity of bone may have relationship with activation of bone growth.

6170-67, Session 11

Investigation on using gold plated micropatterned polymer substrate to build a chemo-mechanical actuator

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Plants have the ability to develop large mechanical force from chemical energy available with bio-fuels. The energy released by the cleavage of a terminal phosphate ion during the hydrolysis of a bio-fuel assists the transport of ions and fluids in cellular homeostasis. Materials that develop pressure and hence strain similar to the response of plants to an external stimuli are classified as nastic materials. This new class of actuators use protein transporters as functional units to move species and result in deformation [Leo et al 2005 (Proceedings of IMECE - 06)]. The ion transporters are hydrocarbons which are formed across the cellular membranes. The membranes that house the ion transporters are aggregates of phospholipids rigidized by cytoskeleton. Reconstituting these nano-machines on a harder matrix is quintessential to build a functional device. Artificial phospholipid membranes or Biliayer lipid membranes (BLM) have poor structural integrity and do not adhere to most surfaces. Patterned arrays of pores made on Poly-propylene glycol-diacrylate (PPG-DA) substrate, a photo curable polymer was made available to us for initial design iterations for an actuator. Hydrophobicity of PPG-DA posed initial problems to support a BLM. We modified the surface of micropatterned PPG-DA membrane by gold plating it. The surface of the porous PPG-DA membranes was plated with gold (Au). A 10nm seeding layer of Au was sputtered on the surface of the membrane. Further gold was reduced onto the sputtered gold surface [Supriya et al(Langmuir 2004, 20, 8870-8876)] by suspending

the samples in a solution of hydroxylamine and Hydrogen tetrachloroaurate(III) trihydrate [HAuCl4.3H2O]. This reduction process increased the thickness of the gold, enhanced its adhesion to the PPG-DA substrate and improved the shapes of the pores. This surface modification of PPG-DA helped us form stable BLM with 1-Palmitoyl-2-Oleoyl-sn-Glycero-3- [Phospho-L-Serine] (Sodium Salt) (POPS), 1-Palmitoyl-2-Oleoyl-sn-Glycero- 3-Phosphoethanolamine (POPE) lipids. The observed ionic resistance of the BLM remained stable and sustained 4 mm water column for the entire 5 hours duration of the experiment. We are currently working on incorporating thiol based phospholipids that enhance the adhesion of BLM on to the Au plated PPG-DA substrate. We will present our results from reconstituting a functional BLM dispersed with ion transporters on gold plated PPG-DA, which is a convenient substrate for micro-patterning and demonstrate the ability to use this scheme for building the micro-hydraulic actuator.

6170-68, Session 11

Coupled transport/hyperelastic model for Nastic materials

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Work is underway to develop high energy density active materials based upon biological processes. These materials utilize the controlled transport of charge and fluid across a selectively-permeable membrane to achieve bulk deformation in a process referred to in the plant kingdom as nastic movements. The nastic material being developed consists of synthetic membranes containing biological ion pumps, ion channels, and ion exchangers surrounding fluid-filled cavities embedded within a polymer matrix. In this paper the formulation of a biological transport model and its coupling with a hyperelastic finite element model of the polymer matrix is discussed. The transport model includes contributions from ion pumps, ion exchangers, solvent flux, and ion channels. This work will form the basis for a feedback loop in material synthesis efforts. The goal of these studies is to determine the relative importance of the various parameters associated with both the polymer matrix and the biological transport components.

6170-69, Session 11

Azo polymers for light-responsive structures and surfaces

C. J. Barrett, McGill Univ. (Canada)

This paper will describe our recent physical and optical studies of multilayer thin films of novel polyelectrolytes which incorporate light-responsive azobenzene. These azo-polyelectrolytes are interesting as they have the capability to be both addressed with lasers as photo-responsive materials (useful for active surfaces, sensing, and signal processing devices for example), and can be self-assembled into structures on the molecular lengthscale in an aqueous environment, using the + and - ionic groups as building blocks. We report here our recent work with assembling a variety of polyelectrolytes, including nonlinear optical azobenzene polyanions, onto Si substrates. Up to 1000 alternating layers have been sequentially deposited, which exhibit good stability to temperature and solvents. We report a variety of deposition geometries explored for confined systems, and show how layer thickness can be controlled by bath pH over more than an order of magnitude on the nanometer lengthscale. A sample application as an optical sensor is presented.

We have prepared such materials as homopolymers, statistical copolymers, and block copolymers, each with a unique suite of photo-controlled properties. Optical, bulk, and surface properties can be interrelated in these materials, allowing studies both of how light can be used to gather new information about surfaces and self-assembled structures, and also how light can be used to influence surface and structural properties. Properties we will demonstrate to be reversibly controlled with light include surface energy and contact angle, film thickness and density (the photomechanical effect), and patterning on the nm lengthscale too by light-induced mass transport.

Many interesting questions about the structure and behaviour of the layers remain unanswered however. We then describe our recent in situ methods to investigate some of these questions, using ellipsometry, surface plasmon resonance spectroscopy, electrophoresis, solid state NMR spectroscopy, and neutron reflectometry.

6170-70, Session 11

Evaluating the mechanical integrity of membrane supported lipid bilayers in a biologically inspired actuator

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Plants naturally achieve large deformation and growth due to the transport of ions and fluids across their cell membranes in response to external stimuli. These biological phenomena inspire the development of a novel actuation device that controls the movement of large-scale structures by pumping fluid across a lipid bilayer from a reservoir into an expansion chamber. The expansion chamber is a pliable material that deforms in response to the rise in pressure as the fluid is pumped inside. As fluid pumps into the expansion chamber, the pressure on the lipid bilayer increases and causes it and the expansion chamber to deform. However, in order for this actuation scheme to be viable, the lipid bilayer must be able to support the pressure that is generated by the biological pumping mechanisms without bursting.

The purpose of this study is to measure the strength of a lipid bilayer membrane when it is subjected to a fluid pressure. Toward this end, a test fixture has been engineered to evaluate the failure pressure of the lipid membrane that is formed on top of a porous polymeric substrate and investigate the performance response of polymerizing lipids in the bilayer confirmation. It is believed that the failure pressure of the membrane will depend on the pore size of the substrate. Moreover, the strength of lipid bilayer will be compared with the mechanical properties that are determined by using atomic force microscopes (Jing, 2002). Finally, the failure properties of a chemically treated phospholipid will also be investigated. Lipid bilayers are composed of small molecules that interact in response to polar, ionic, and Van der Waals forces. For increased stability 1-Palmitoyl-2-Oleoyl-sn-Glycero-3-Phosphoethanolamine (POPE) is functionalized with an acrylate head group and then polymerized in the bilayer confirmation after exposure to ultraviolet irradiation. Our initial studies show that a bilayer formed from unfunctionalized POPE on a membrane with an array of 50 micrometer pores with 50 % porosity will support a pressure head of approximately 700 Pa before failure. It is hypothesized that POPE polymerized in the bilayer confirmation will be stronger than the unfunctionalized POPE.

6170-71, Session 12

Hybrid EAPap actuator coated with multiwall carbon nanotubes

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Electro-Active Paper (EAPap) materials based on cellulose are attractive for many applications because of their low voltage operation, lightweight, dryness, low power consumption. In addition, EAPap materials are bio-degradable that is important property for artificial muscle actuators for biomimetic with controlled properties and shape. The construction of EAPap actuator has been achieved using the cellulose paper film coated with thin electrode layers. This actuator showed a reversible and reproducible bending movement. In order to improve both force and displacement of this, complementary conjugated novel material, composed of conductive polymer and carbon nanotubes, is coated on both sides of EAPap. This composite coated EAPap is termed as hybrid EAPap. Used composite consist of multiwall carbon nanotubes (MWNT) and polyaniline (PANi). It is expected that the use of MWNT can enhance the stiffness of the tri-layered actuator, thus improving the force output. Furthermore, the presence of the MWNT/PANi electrodes may increase the actuation performance of the EAPap material. MWNTs are dispersed in NMP (1-Methyl-2-pyrrolidine), and the resulting suspension is mixed and sonicated with anion doped PANi. Obtained MWNT/PANi/NMP solution is cast on the EAPap by spin coating, and it is dried in an vacuum oven. The effect of processing parameters on the final performance of the composite electrodes is assessed and quantified in terms of the electrical conductivity under dc and ac measurement conditions. The actuation output of the MWNT/PANi/EAPap samples is tested in an environmental chamber in terms of free displacement and blocked force. The performance of the hybrid actuators is also investigated in terms of frequency, voltage, humidity and temperature to help shed light on the mechanism responsible for actuation. Comparison of these results in that of the EAPap with PANi and EAPap are also accomplished.

6170-72, Session 12

In-plane piezoelectricity of cellulose EAPap material

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Electro-Active Paper (EAPap) has been interested in due to its merits in terms of lightweight, dry condition, large displacement output, low actuation voltage, low power consumption and biodegradability. EAPap actuator has been made with cellulose material. Cellulose fibers are dissolved into a solution and extruded in a sheet form, and a think gold electrodes are made on it. Regarding the actuation mechanism of EAPap actuator, migration and dipole orientation effects are currently claimed. Ions and free water molecules in EAPap material can migrate in the presence of electric field. Through the thermally stimulated current test, a dipole orientation effect on EAPap material has been observed. Generally, migration effect causes pure bending deformation due to the expansion of cathode side. Dipole orientation in cellulose material cause shear piezoelectricity, and this property can cause a bending deformation, so call shear deformation. These two deformations may result in different patterns of deformation.

Therefore, we intended to investigate the piezoelectricity of EAPap in terms of in-plane strain with frequency and humidity. Different frequency and humidity may affect the in-plane deformation pattern, and this investigation will give a clue that can explain the actuation principle of EAPap actuator.

6170-74, Session 12

Large electromechanical response of a silicone elastomer containing PPV

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Electrorheological properties of PDMS gel and PPV/PDMS blend were investigated experimentally under an oscillatory shear mode at the temperature of 27 0C to determine the effects of crosslink ratio, electric field strength and doping level. For the pure PDMS gels, the storage modulus, G', increases with increasing crosslinking ratio and electric field at all frequencies between 0.1-100 rad/s. When an electric field is applied, the polymer molecules become polarized resulting in the interaction through the electrostatic force between the polarized PDMS molecules. The PDMS gel system with the crosslinking ratio of 0.01 possesses the highest G sensitivity to electric field. For the PPV/PDMS blends (PPV/PDMS_10), the dynamic moduli, G' and G", are higher than those of pure PDMS in the absence of electric field because PPV particles act as a filler in PDMS matrix. The G' sensitivity of PDMS increases up to 35 % at the electric filed strength of 2 kV/mm. Moreover, the doped PPV/PDMS blend (doped PPV (1:10)/PDMS_10) shows the highest G' sensitivity (170 %) due to interacting electrostatic forces between electric field induced dipole moments of the conductive molecules.

6170-75, Session 12

Physics of transduction in ionic liquid-swollen Nafion membranes

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Ionic polymer transducers are a class of electroactive polymers that are able to generate large strains (1-5%) in response to low voltage inputs (1-5V). Additionally, these materials generate electrical charge in response to mechanical strain and are therefore able to operate as soft, distributed sensors. Traditionally, ionic polymer transducers have been limited in their application by their hydration dependence. This work seeks to overcome this limitation by replacing the water with an ionic liquid.

Ionic liquids are molten salts that exhibit very high thermal and electrochemical stability while also possessing high ionic conductivity. Results have shown that an ionic liquid-based ionic polymer transducer can operate for more than 250,000 cycles in air as compared to about 2,000 cycles for a water-based transducer. The current work examines the mechanisms of transduction in ionic liquid-swollen transducers based on Nafion polymer membranes. Specifically, the morphology and relevant ion associations within these membranes are investigated by the use of small-angle X-ray scattering (SAXS), Fourier transform infrared spectroscopy (FTIR), and nuclear magnetic resonance spectroscopy (NMR). These results reveal that the ionic liquid interacts with the membrane in much the same way that water does, and that the counter-cations of the Nafion polymer are the primary charge carriers. The analytical techniques are used to develop a physical interpretation of ion transport within the ionic liquid-swollen Nafion membranes and this model is compared to the macroscopic transduction behavior to elucidate the fundamental coupling mechanisms. Improved actuation and sensing performance is demonstrated in the ionic liquid-swollen membranes as compared to the traditional water-swollen materials. High-cycle testing of the new transducers demonstrates the improved stability made possible by the use of an ionic liquid.

6170-76, Session 12

Variably-stiff engineered cellular materials for morphing structures

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Structures that can physically adapt to fulfill many roles can enable a new generation of high performance systems. For many important shape changing applications, including morphing aero structures, the key to achieving large benefit is large changes in structural geometry and stiffness with minimized energy expended during transformations. Currently, few material choices exist which can accommodate the deformation required in the most demanding applications. However, the most deformable materials presently available, polymer elastomers, also have poor stiffness and toughness properties. We have identified an alternative approach to achieving ultra-large deformations using materials with modest reversible deformation attributes. This approach employs cellular engineered structures to achieve effective linear extensions of \>50% and area changes greater than 100%. While many materials may be used as a basis for these engineered structures, variable stiffness composites based on shape memory polymer matrices are an excellent candidate due to their combination of relatively high stiffness and reversible strain accommodation. We have used existing analytical models combined with finite element analysis to determine optimized shapes and geometries for cellular structures which accommodate large deformation through elastic buckling of cell walls. Finite element simulations are supported with experimental data of prototype high deformation cellular materials fabricate using shape memory polymer and carbon fiber. Results demonstrate large, volume-changing deformation (~100%) with Poisson ratios ranging from negative to positive values using auxetic cellular geometry. We have also investigated cellular materials that incorporate both constant and variable stiffness elements to accommodate large deformation in-plane while resisting out-of-plane deformations. These types of materials may be especially critical for aero surfaces which must transfer lift and drag loads to the structure at all times.

6170-77, Session 12

Electroactive polymer composites - analysis and simulation

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The class of electroactive polymers have been developed to a point where real life applications as "artificial muscles" are conceivable. These actuator materials provide attractive advantages: they are soft, light-weight, undergo large deformations, possess fast response time and are resilient. However, wide-spread application has been hindered by their limitations: the need for large electric field, relatively small forces and energy density. It is now recognized that the limitations arise from poor electro-mechanical coupling in typical polymers. This in turn is related to the fact that the typical polymers have a small ratio of dielectric to elastic modulus (flexible polymers have low dielectric modulus while high dielectric moduli polymers are stiff).

We carry out preliminary calculations for different classes of composites. For the class of sequentially laminated composites explicit expressions relating the electrostatic excitation to the overall mechanical response are derived. These calculations demonstrate that the electromechanical coupling can be improved by considering non-homogeneous electromechanical actuators. In particular, we show that the overall response of a composite actuator can be better than the responses of its constituents. These findings are in agreement with recent experimental work showing that the limitations of these actuators can be overcome by making composites of flexible and high dielectric modulus materials (Huang, Zhang, deBotton and Bhattacharya 2004, Applied Physics Letters, 84, 4391).

We also carry out numerical simulations of electroactive fiber composites with periodic hexagonal cells. These calculations are based on finite element simulations by application of ABAQUS. We find that, in a manner resembling the purely mechanical case, the analytical results for the coupled electromechanical problem for the class of sequentially laminated composites are in agreement with the FE simulations for the fiber composites.

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6171-01, Session 1

Piezoelectric-based power sources for harvesting energy from platforms with low-vibration frequencies

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This paper presents a new class of highly efficient piezoelectric based energy harvesting power sources for mounting on platforms that vibrate at very low frequencies as compared to the natural frequency of the resonating elements (U. S. Patent is pending). These energy harvesting power sources have a very simple design and do not require any tuning for each application to match the frequency of the platform vibration.

The developed method of harvesting mechanical energy and converting it to electrical energy overcomes problems that are usually encountered with harvesting energy from the low frequency vibration of various platforms such as ships and other platforms with similar vibratory (rocking) motions. Omnitek Partners has designed several such energy harvesting power sources following modeling and simulation studies and optimization of their main design parameters and is currently in the process of constructing several prototypes for testing. The developed designs are modular and can be used to construct power sources for various power requirements. The amount of harvested power is obviously dependent on the frequency and amplitude of vibration of the platform, and the size and mass of the power source.

6171-02, Session 1

Studies of acoustic-electric feed-throughs for power transmission through structures

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There are numerous engineering design problems where the use of wires to transfer power and communicate data thru the walls of a structure is prohibitive or significantly difficult that it may require a complex design. Using physical feedthroughs in such systems may make them susceptible to leakage of chemicals or gasses, loss of pressure or vacuum, as well as difficulties in providing adequate thermal or electrical insulation. Moreover, feeding wires thru a wall of a structure reduces the strength of the structure and makes the structure prone to cracking due to fatigue that can result from cyclic loading and stress concentrations. One area that has already been identified to require a wireless alternative to electrical feedthroughs is the container of the Mars Sample Return Mission which will need wireless sensors to sense pressure leak and to avoid potential contamination. The idea of using elastic or acoustic waves to transfer power was suggested recently by [Y. Hu, et al., July 2003]. This system allows for the avoidance of cabling or wiring. The technology is applicable to the transfer of power for actuation, sensing and other tasks inside any sealed container or vacuum/pressure vessel. An alternative approach to the modeling presented previously [Sherrit et a., 2005] used network analysis to solve the same problem in a clear and expandable manner. Experimental tests on three different designs of these devices were performed. The three designs used different methods of coupling the piezoelectric element to the wall. In the first test the piezoelectric material was bolted using a backing structure. In the second test the piezoelectric was clamped after the application of grease and finally the piezoelectric element was attached using a conductive epoxy. The mechanical clamp with grease produced the highest measured efficiency of 53% however this design was the least practical from a manufacturing viewpoint. The power transfer efficiency of conductive epoxy joint was 40% and the stress bolts(12%). The experimental results on a variety of designs will be presented and the thermal and non-linear issues will be discussed.

6171-03, Session 1

Development of a smart substrate for a laser powder deposition process

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The nonuniform heating and cooling associated with laser powder deposition fabrication and repair processes can leave significant residual deformations/stresses both in the part and the substrate. This results in geometric inaccuracies and/or possible structural deficiencies. This paper takes a “smart-structures” approach to address this problem. An active-control method is investigated, in which piezoelectric (and/or mechanical) actuators provided on the substrate are used sequentially to deform and undeform a substrate through deposition with the goal of minimizing the residual deformations/stresses in the part. As the laser moves over the substrate depositing the part layers, the voltages on the actuators are varied correspondingly. If the overall plate deformations are small enough, it is possible to compute a sequence of actuator voltages that will result in negligible residual deformations/stresses in the substrate.

In the work described in this paper, the goal has been to study a simpler non-real time strategy where a one-time actuation voltage is applied to pre-deform the substrate in a sense opposite to that caused by the laser-deposited part. For example, for moderately high straight-line thin builds the substrate and the part generally are found to have a concave up residual deformation. The actuators are therefore excited to provide a concave down deformation on the substrate before beginning the part deposition. The voltages are maintained through the duration of the build, and are gradually reduced as the part cools down gradually, while the thermal effects are trying to undo the actuator-caused deformation. The voltages are reduced until the substrate/part is flat and are left at this level until the part is separated from the substrate.

In the experiments to be described, thin-walled builds deposited on rectangular-plate substrates were considered. Different actuation configurations based on piezoelectric actuators were first evaluated using linear theory to be outlined in the paper. An additional scheme based on a mechanically actuated substrate was also investigated. Tests on steel builds with this scheme showed that with predeformations using this approach, the residual deformations in a thin-walled fabricated part could be reduced by about 73%. Further tests with Titanium builds are underway.

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6171-04, Session 1

Acoustic challenges of the A400M for active systems

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In some vehicle types interiors tonal noise with high sound pressure level (up to 120 dB) occurs at low frequencies (f < 500 Hz). Typical examples are propeller driven aircrafts for which the excitation frequencies are given by the blade pass frequency (BPF) and its higher harmonics. The high tonal noise levels at these frequencies can occur because the blades’ profiles are only optimized in terms of aerodynamics. The acoustic properties are usually not taken into account. In order to obtain an acceptable noise level, and to guarantee both work-security and comfort in the aircraft interiors, passive methods are commonly used - e. g. adding material with high damping or vibration absorbers. Especially when low frequency noise has to be reduced this solution results in a lot of unwanted additional weight. In order to avoid this extra weight, the concept of active noise reduction (ANR) would be a good option in aircraft interiors. In this field extensive research projects were carried out in the past decades. As a result, commercial ANR systems are nowadays used in some smaller passenger airplanes. For large transport aircrafts the sound pressure level in the cargo can reach up to 110 dB(A)- as measured in a certain type of four propeller military transport aircraft - when not using noise reduction of any kind. For such high tonal noise levels inside a large cargo area ANR-systems are so far not available.

The paper discusses different possible methods to reduce the low frequency noise in an aircraft cargo. One is the use off tuned vibration absorbers (TVA) mounted on the airframe. The resulting noise reduction is estimated by vibroacoustic finite element calculations. In order to abide to the work-security rules, the noise level inside the semi closed loadmaster working station (LMWS) must be reduced to 86 dB(A). The paper describes the design of an ANR system that could be used to control the sound pressure level inside the LMWS. The concept is verified by experimental investigations within a mock up of the LMWS.

6171-05, Session 1

EB irradiation induced multiproperties of thin film plate of transparent inorganic materials for liquid crystal display

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The transparent glassy ceramics are used for thin film plate of large-size crystal

liquid TV. However it is difficult to product the thin plate with ultra thin and large-size because of brittleness of glass. In addition, wettability is a serious problem between liquid crystal and glass. Low energy electron beam (EB) irradiation, recently has applied for surface layer improvement for polymer, also enhanced wettability, mist resistance and strengthening for transparent inorganic materials. On the other hands, the EB strengthening and wettability of the transparent inorganic materials have been explained as caused by stress relaxation and charging induced by dangling bond formation formed by EB irradiation. Thus, the contributions of EB irradiation induced to multi-properties of thin transparent inorganic materials have applied for liquid crystal display are investigated.

6171-06, Session 2

Reaction force of percussive corer, rotary-friction corer, and rotary-percussive corer

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Future NASA exploration missions will increasingly require sampling, in-situ analysis and possibly the return of material to Earth for further tests. To address this objective, effective and optimized drilling techniques are needed. This requires developing comprehensive tools to be able to determine analytically what takes place during the operation and what are the control parameters that can be enhanced. In this study, three types of coring techniques were studied and were identified as potential candidates for operation from a future Mars Sample Return (MSR) mission rover. These techniques include percussive, rotary-friction, and rotary-percussive coring. Theoretical models were developed to predict the dynamic reaction forces transmitted from these three types of corers to the robotic arms that hold them. The predicted reaction forces will then be used in a dynamic simulation environment to simulate a representative corer tool to obtain a best estimate of a tool that can be operated from a small rover. The predicted dynamic reaction forces will be presented in this paper.

6171-07, Session 2

Ultrasonic/sonic gopher for subsurface ice and brine sampling: analysis and fabrication challenges, and testing results

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Rock, soil, and ice penetration by coring, drilling or abrading is of great importance for a large number of space and earth applications. Proven techniques to sample Mars subsurface will be critical for future NASA astrobiology missions that will search for records of past and present life on the planet. A required technology study is planned for Lake Vida in the Dry Valleys, Antarctica, which is serving as a Mars analog. The ice layer on Lake Vida in the Dry Valleys is estimated to be 20-meter thick where below 16-m depth there is a mix of ice and brine, which has never been sampled directly due to logistical constraints. An Ultrasonic/Sonic Drill/Corer (USDC) has been developed as an adaptable tool for many of these applications [1]. The USDC uses a novel drive mechanism to transform the ultrasonic or sonic vibrations of the tip of a horn into a sonic hammering of a drill bit through an intermediate free-flying mass. The USDC design was modified to fabricate an Ultrasonic/Sonic Ice Gopher that is able to core down to the 20-m depth for in situ analysis and sample collection. Coring ice at -20oC as in Lake Vida suggests that it is a greater challenge and current efforts are focused on the problems of ice core cutting, ice chip handling and potential ice melt (and refreezing) during drilling. The analysis and fabrication challenges and testing results will be presented in this paper.

[1] Bar-Cohen, Y., Sherrit, S., Dolgin, B., Bao, X., Chang, Z., Krahe, R., Kroh, J., Pal, D., Du, S., Peterson, T., "Ultrasonic/Sonic Driller/Corer(USDC) for planetary application," Proc. SPIE Smart Structure and Materials 2001, pp. 529-551, 2001.

6171-08, Session 2

USDC-based rapid penetrator of packed soil

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Environment protection requires more testing and analysis tools. To detect chemical containers or other objects embedded in soil and avoid possible damages of them, a penetrator of packed soil operated under low preload was developed. The design was based on the ultrasonic/sonic driller/corer (USDC) device developed in the NDEAA lab at JPL[1]. In the penetrator, a small free-flying mass is energized by a piezoelectric transducer and impacts a rod probe on its shoulder at frequencies of hundreds times per second. The impacts help the probe to penetrate the packed soil rapidly. A great reduction of the needed preload was achieved by this penetrator. The details of the design of the penetrator, numerical analysis of the USDC mechanism and the results of performance tests will be presented.

[1] Bar-Cohen, Y., Sherrit, S., Dolgin, B., Bao, X., Chang, Z., Krahe, R., Kroh, J., Pal, D., Du, S., Peterson, T., "Ultrasonic/Sonic Driller/Corer(USDC) for planetary application," Proc. SPIE Smart Structure and Materials 2001, pp. 529-551, 2001.

6171-09, Session 2

A miniature bimorph piezoelectrically actuated flow pump

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Precision flow pumps have been widely studied over the last three decades. They have been applied in the areas of Biology, Pharmacy and Medicine in applications usually related to the dosage of medicine and chemical reagents, such as continuous insulin injection in diabetic patients with elimination of peaks and valleys of this dosage, common in the usual treatment. Another motivation for flow pump studies consists in overcoming the present matters found in the traditional biological fluid pumping techniques, the most relevant of which could be the death of microorganisms and cells in the fluid during the process, caused by the high pressure or even the turbulence generated in the flow. The high hemolisys indices (death of hematias) in bypass surgeries is an example. In addition, thermal management solutions for electronic device cooling have also been recently developed using these kinds of pumps offering better performance with low noise and low power consumption.

In this work, a novel configuration of a miniature piezoelectric actuated flow pump has been studied and it will be presented. Its working principle is based on the use of a bimorph piezoelectric actuator inserted in a fluid channel to generate flow. The complete cycle of pump development was conducted, consisting in designing, manufacturing, and experimental characterization steps.

In the design step, computational simulations were applied to perform sensitivity studies and optimization process by using commercial software. To simulate and study the fluid-structure interaction inside the pump, as well as the bimorph piezoelectric actuator behavior, the ANSYS(r) finite element analysis software has been applied. A sensitivity study was conducted using computational simulations to analyze effects of parameter variation of geometry and applied voltage in the pump behavior. This study also gave information to guide the design of pump electronic control modules allowing us to achieve a desired flow rate by varying the frequency and amplitude of the applied voltage. In addition, an optimization process was carried out through Altair Hyperstudy(r) software to find a set of parameter values that maximizes the pump performance measured in terms of flow rate. This software interfaces with ANSYS(r) software allowing the integration of finite-element analysis with an optimization algorithm.

The prototype manufacturing was guided based on computational simulations. Both pump case and bimorph piezoelectric actuator were manufactured. A CNC machine tool and a proper ceramic cutting tool were used in the manufacturing. Electronic circuits for pump electrical excitation and control were developed and implemented. They include a signal generator that works as a source of a sinusoidal wave with controlled amplitude and frequency, and an amplifier to raise excitation voltage levels to the desired values.

Load-loss and flow characterization experimental tests were conducted, generating data that allows us to analyze the influence of frequency and amplitude parameters in the pump performance. The experimental set also allowed us to obtain the curve of pressure as a function of pump flow rate.

Comparisons among numerical and experimental results were made to validate the computational results and improve the accuracy of the implemented models.

6171-10, Session 2

Integration of smart materials into high-volume manufacturing methods

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The integration of smart materials such as piezoelectric materials and shape memory alloy to structures has been typically limited to a bonding process that occurs in a secondary operation. Such operation is not only costly for high volume applications, but it also has the potential of degrading the performance of the actuator or sensor due to the bonding agent selected. The work presented here explores the integration of piezoelectric and shape memory alloy materials using an injection molding process. The process used is the one typically developed for large automotive components such as bumpers, instrument panels and other body panels. Different materials were evaluated, both plastics and smart materials. Tem-

perature and flow rate were also changed to see the effects on the durability of the materials. Piezoelectric materials were evaluated both bare and packaged. Similarly, shape memory alloy wires were evaluated with and without coating. Both electrical and mechanical properties were tested. Key parameters included, void content, geometric location and tolerance, strain transfer and peal strength. It was found that good integration of piezoelectric materials could be achieved, and improved electro-mechanical properties could be achieved than a two step produce and apply operation. Integration of screen printed electrical circuits for electrical connectivity was evaluated for piezoelectric materials. In conclusion, a step forward was made in developing a multifunctional material based upon smart materials and conventional high volume manufacturing process. Examples of parts using this methodology were automotive bumpers and automotive instrument panels.

6171-11, Session 3

Real-time pressure monitoring for dynamic control during paper mill operation using fiber optic pressure sensors

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Fiber optic pressure sensors were integrated into the grinding plates of an operational paper pulp mill for real-time monitoring of the pulp grinding process. Online system monitoring will allow smart, active control of the grinding plates thereby improving the quality and consistency of the pulp produced. Sensors were constructed and calibrated for use in the harsh environment of an operating paper pulp grinder. The sensors were 1.65mm in diameter including titanium housing, and were installed directly into the grooves of the grinding plates. The sensing elements were flush-mounted with the wall and exposed to the wood pulp slurry. Five sensors were calibrated up to 1000psi. During operation, pressure was sampled at 500kHz, and pressure spikes up to 175psi were observed. Pressure pulses measured are due to the relative motion between the grooves and channels on two pulp grinding plates. The consistency, size distribution, and quality of paper pulp exiting from the grinder are directly related to the distance between the channels on the two rotating elements. The pressure pulses produced are also proportional to the distance between channels. Therefore, by monitoring pressure fluctuations, grinding elements can be dynamically controlled thereby producing a “smart mill.”

6171-12, Session 3

Damage growth monitoring for a bonding layer of the aircraft composite structure

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This paper presents a part of a development with respect to damage monitoring technologies for the bonding layer of the aircraft composite structure using the FBG optical fiber sensor/PZT actuator hybrid sensor system. We verifies the affordability of our novel monitoring system using FBG optical fiber sensor embedded in the bonding layer. Also, we confirm that the change of the elastic wave depends on the damage growth behavior in the bonding interface of the composite structure using the coupon and the structural element specimens.

In this paper, it is verified that a damage initiation and growth can be explained as a simple index, which is named “Damage Index”, obtained by the analysis of the received wave form. Furthermore, we develop the software that can visualize the damage initiation and growth. After we verifies the validity of the developed damage monitoring system in coupon specimens, we also demonstrates that the judgment of a damage initiation and growth is possible in structural element test articles with artificial damage which simulates aircraft bonding structure.

6171-13, Session 3

Damage detection of advanced grid structure using multipoint FBG sensors

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There is growing demand for lightweight structures in aircraft systems for energy and cost saving. Composite materials such as graphite fiber reinforced plastics are promising candidates to meet these requirements. However, since extremely high reliability is required for aircraft systems, composite materials have not been fully applied especially in commercial aircraft. A structural health monitoring system is the most effective technology to solve this problem. The authors are developing a new lightweight grid structure for aircraft applications equipped with a health monitoring system utilizing FBG (fiber Bragg grating) sensors. A grid structure, comprising multiple interconnected ribs in a truss-like arrangement, has a very simple path of stress, which is easily detected with FBG sensors embedded in the ribs.

A specimen of highly reliable advanced grid structure was fabricated to demonstrate damage detection. The size of the specimen was 525Å~550 mm and the number of embedded FBG sensors were 29. The strain distribution of the panel was measured using FBG sensor network under loaded conditions. The artificial damage in the rib of the specimen was successfully detected by comparing the strain distribution before and after the introduction of the damage.

6171-14, Session 3

Control of sheet-metal forming processes with piezoactuators in smart structures

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The most important task at sheet metal forming is the optimisation of the material flow. Every cull part increases the production costs. By the application of the multipoint cushion device in connection with an elastic blankholder it is possible to influence actively the material flow at the flange range. The explicit enhancement of the deformation ratio is achievable, especially at the novel high strength materials in the car body production.

State of the art are multiple draw pins to initiate the force on selected points at the blankholder.

The cushion plate, situated between hydraulic pressure rollers and draw pins, admittedly does not allow an optimal force allocation.

The replacement of selected draw pins by piezoactuators, which can generate high forces, enables a systematic control of the force progression at critical forming areas during sheet draw-in. The system, consisting of piezostack actuator, dynamometer and components for the force initiation, was realized as a compact unit with low resilience. A force measurement by the inherent sensory properties of the piezostack actuator is intended. The consequential conversion of this concept enables a reduction of hydraulic components and eventually leads to a cheaper one point cushion device. In the context of a research project at the Fraunhofer Institute for Machine Tools and Forming Technology Chemnitz in cooperation with a partner from the automobile industry first results could be achieved. Ad hoc a draw pin was replaced by a highly stressable piezoactuator, which is integrated in a force control cycle. The force progression during the sheet draw-in could be adjusted accurately to a predetermined master curve. The master curve itself was taken up in the unregulated process and represent the quality criteria of a transformed property part. On the basis of the real-time simulation tool “MATLAB Simulix XPC-Target” an adjustment concept was realized, which connects the specific signals of the press control like tappet way, die cushion position, die cushion force with reference force (master curve) and actual force of the piezoactuator.

6171-15, Session 3

High integrity adaptive SMA components for gas turbine applications

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The use of Shape Memory Alloys (SMAs) has grown considerably, but is still largely restricted to niche areas and small scale applications. They have been under serious development for aerospace applications for over 15 years, predominantly aimed at airframes. They offer major advantages for adaptive gas turbine components, but the harsh environment with high loads, temperatures and vibration excitation provide considerable challenges which must be met whilst still delivering high integrity, light weight, aerodynamic and efficient structures.

A novel method has been developed which will deliver high integrity, stiff mechanical components which can provide massive shape change capability without the need for conventional moving parts.

A stiff structure requires large volumes of SMA to move it. A fully structurally integrated concept has been developed, where the SMA and parent structure work in opposition to give spring loaded, flexural actuation, but work together against external loads. This provides a light weight, robust structure providing large flexural actuation, but is very stiff against external loads. The lead application is for an adaptive serrated engine nozzle for noise reduction. The sub element component is 150mm long and provides 35mm of movement at the tip, but will only deflect around 1mm when subjected to operational gas loading. The application will provide a mechanism for noise reduction at take off and climb, but retract at cruise to remove the considerable fuel burn penalty which would otherwise occur.

The challenges are in providing large scale, consistent SMA parts which can be fully integrated into a structure. This requires considerable material and production capability, joining and design methods. All are at an advanced stage of devel-

opment.

The technology promises to provide significant advantages for applications in a gas turbine such as shape change aerofoils, heat exchanger controls, and intake shapes. The same mechanism should be directly applicable to other areas such as air frames, automotive and civil structures, where similar high integrity requirements exist.

6171-16, Session 3

Microstructure of the crystals generated in borate glass irradiated by femtosecond laser pulses

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This paper deals with the microstructure of the generated crystals in borate glass by femtosecond laser irradiation, Raman spectroscopy was used to study the distribution of the high temperature and low temperature phases of barium metaborate crystals produced in the borate glass, and the mechanism was discussed.

6171-17, Session 4

An MR fluid-based orthopaedic active knee brace

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According to the American Academy of Orthopaedic Surgeons, knee braces fit into several categories: (1) prophylactic knee braces which are intended to prevent or reduce the severity of knee injuries in contact sports; (2) functional knee braces which are designed to provide stability for unstable knees; and (3) rehabilitative knee braces which are designed to allow protected and controlled motion during the rehabilitation of injured knees. A fourth category includes patellofemoral knee braces, which are designed to improve patellar tracking and relieve anterior knee pain [1]. For the topic of discussion, however, prophylactic and functional knee braces are the only appropriate ones. These two types of knee braces have their advantages and disadvantages. One disadvantage is that the user has no control over the joint resistance of the brace. If the user wants to increase or decrease the joint resistance in order to change the pressure on the injured area they will have to replace the existing joint or purchase a customized unit which can be costly. Another disadvantage is that functional knee braces can cause a short-term decrease in physical capability. This stems from the fact that during rehabilitation the functional knee brace does not exercise the leg while it puts pressure on it and can decrease blood flow.

To address these disadvantages a magnetorheological (MR) device can be applied to either one of these knee braces. MR devices have been applied to various fields such as passenger protection systems, prosthetics and automotive suspension. In the current application a rotary shear joint will be developed using MR fluid as the semi-active element of a knee brace (see figure 1). There it will serve as a resistance against tension and flexion of the lower limb. Since an MR fluid has a controllable yield stress as a function of input field, one can actually have control over the resistance of the knee brace. Initial designs have shown the ability to produce resistance load torques up to 50 Nm. Two knee brace models are being developed in this research. The first model is purely passive and uses stacking of thin magnets to get the desired field and thus the desired load torque. This allows control of the strength of the magnetic field of the magnets and in turn gives the user control over how much yield stress the MR fluid will produce. Football players as another example use prophylactic knee braces to support their knees against anteposterial rotation. In this case the MR fluid can be applied with an actuator to detect the anteposterial rotation, harden the MR fluid to prevent further rotation and in turn prevent injury.

The idea is to incorporate and MR fluid into a three-plate joint. The MR fluid will be soaked into a sponge to prevent leakage out of the plates. For the design four plates will be used on each knee which the MR fluid will actively work against (see figure 2). In order to get the fluid's resistance to flow rare-earth magnets will be applied to the outermost plates on each knee. As the number of magnets increases the fluid's flow resistance will increase and a greater torque will be required to rotate the MR joint.

In order to design this device, however, a particular torque that was needed was chosen and then based on that torque and the number of magnets a set of design equations was analytically developed to find the geometric properties corresponding to this torque. Specifically, the "minimum active fluid volume" technique was implemented to find the required radius of the plates in the device. A design torque of 50 Nm was used to obtain the required dimensions of the device [2-4]. Once designed, a prototype was built and tested. This device is expected to provide an attractive means to develop active knee braces that are easy to use, easy to control and offer functional versatility for various needs as described before.

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6171-18, Session 4

Magnetorheological fluid-based automotive steer-by-wire systems

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Recently the concept of replacing hydraulic and mechanical systems of automobiles by proven aerospace technology has been under consideration. A system that controls automotive steering by means of computer-controlled electronic signals instead of a direct linkage through the steering column is called a steer-by-wire system. The term is reminiscent of fly-by-wire, systems used for controlling commercial and military aircraft for more than a decade. For more than a century, drivers controlled vehicles under direct actuation by mechanical, hydraulic or pneumatic systems. If such a system fails the consequences could affect the safety of the vehicle or passengers. Additionally, the components associated with these systems are bulky and add unnecessary weight to the vehicle. In general steer-by-wire systems, like the one described in this work, are part of a larger drive-by-wire system being slated for next generation automobiles. In a drive-by-wire system, the driver controls are simply inputs to a computerized system rather than directly commanding the vehicle functions. The idea is to remove the mechanical linkages between the controls of a car and replace it with electronic devices. Thus instead of a direct connection to the steering mechanism, accelerator, and brake, the electronic systems will send commands to a central computer, which will control these vehicle functions(Figure). [1-3]

Steer-by-wire offers improvements in safety with the removal of the steering column, therefore improves the crash performance of the vehicle. Other benefits include corrective steering to improve stability control, tunable steering feel, reduction in vehicle weight, better fuel consumption, and enhanced vehicle handling leading to a decrease in the number of road accidents. The main problem with steer-by-wire systems lies in the fact that without the steering column and its direct connection to the wheels, there is no mechanism for tactile feedback to the driver. Feedback would certainly be required in order to give the driver meaningful information about what is happening on the road. For instance, feedback on irregularities in the surface of an unpaved road is transmitted via movement of the steering wheel. Furthermore, the force feedback allows for the communication of cautionary information to the driver through vibration or cessation of operation, such as a warning when the driver is deviating from laneor has struck an unseen obstruction in the road.

The idea of this paper is to design a magnetorheological fluid based damper for the steering wheel to provide sensory feedback to the driver. The advantages of using MR fluids in haptic devices stems from the increase in transparency gained from the lightweight semiactive system and controller implementation. The most notable negative is the "sticky wall" phenomena. The work in this study overcomes these limitations by the addition of variable compliance to the system and nonlinear controls.

There are a number of simple models used to describe MR fluid operation such as Bingham model [4] and Herschel-Bulkley viscoplasticity model [5]. While present rheological based modeling techniques of MR fluids work well for modeling dampers, clutches, and brakes, there are some advanced applications (e.g. tactile and force feedback systems) that require higher fidelity models, force feedback, and variable compliance. A microstructural, kinetic theory-based model of MR fluids has been developed [6]. For modeling these composite systems, dumbbell models in which two beads joined by an elastic connector were investigated. The iron particles are modeled as elastic dumbbells suspended in a carrier fluid. Microscale constitutive equations relating flow, stress, and particle orientation are produced. These new models for MR fluids are three dimensional and applicable to any flow geometry. The model developed in this study is also fully vectorial and relationships between the stress tensor and the applied magnetic field vector are fully exploited.

Because of the large range of forces necessary a number of different MR fluids are employed: Carbonyl iron powder with two different particle size ranges (2-5 and

4-7 micron) mixed with silicone oils with five different viscosities (eta=0.00935, 0.1906, 0.34055, 0.974, and 12.1875 Pa.s) with different weight ratios of iron particle to silicone oil are used to make more than 30 different samples of MR fluids. These MR fluid samples are used in the designed MR sponge damper [5] and tested in a MTS machine commonly used for tensile tests. The resulting force-velocity graphs of the damper for twelve varieties of MR fluids are used to determine the damper with the greatest range (in terms of force).

The number of MR damper spools, gage size, and damper dimensions to be used in the design of MR damper will be found by solving an optimization problem. A full interactive toolbox will be developed for solving this optimization problem (Figure 2). The results will be compared to that of a finite element modeling and then the damper will be designed and manufactured for the experimental tests.

In order to simulate the road surface conditions a computer based toolbox will be developed to model the vehicle wheels and the obstacles in a graphical environment. As the operator is controlling the vehicle by the steering wheel, the MR damper will be activated when the vehicle wheel hits the obstacles in the computer simulated program. For this application of MR dampers we'll have the master (steering wheel) in the real world, while the slave (vehicle) is in a virtual reality environment. The steering wheel has an encoder measuring the steering wheel angle. For the sake of redundancy, another revolving digital sensor could be used. The MR damper will be connected to the steering wheel shaft to give some feedback to the driver (Figure3). By applying a current to the MR damper, it is possible to generate a resistance torque when the driver rotates the steering wheel. The torque is dependent on the steering wheel angle or the difference between the steering wheel angle and the angle of vehicle wheels. There should also be a speed dependent behavior, restricting the turning angle at high speed.

6171-19, Session 4

Active control of train bogies with MRF dampers

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In this paper a rail vehicle with active suspension is studied. A passenger-wagon bogie was modeled by ADAMS Rail to analyze the dynamic response of the suspension system. In order to design and implement the controller, ADAMS Control is employed. Magnetorheological Fluid (MRF) dampers were used as active dampers to suppress vibrations adaptively. They have been investigated in primary and secondary suspensions of passenger-wagon bogies. Accelerometers were employed as sensors in our control system. An optimization procedure is performed to obtain the optimal suspension components and their placements. The objective of the control system is to reduce wheel-rail forces. Results showed that MRF is capable of reducing vibration and rail-wheel forces. Particularly, in curved tracks the active suspension system using MRF showed its significance over traditional passive suspensions. It was shown that the controller reduced the wear rate of wheels as well. The control system also demonstrated significant improvement of rail vehicle stability in addition to increase in travel speed and passenger comfort. The comfort index of ADAMS Rail showed that the proposed active suspension system is greatly increasing the passenger comfort especially in high speeds. The control system design and implementation and detailed results will be presented in the full paper.

6171-20, Session 5

Shape memory polymer tooling

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Cornerstone Research Group, Inc. (CRG) has demonstrated the feasibility of filament winding complex-curved composite shapes on shape memory polymer (SMP) mandrels. SMPs can exhibit a radical change from a rigid polymer to a flexible, elastic state, and then back to a rigid state under thermal stimuli. SMP mandrels for filament winding and fiber placement allow for a quick, easy, reusable, and low-cost mandrel system. CRG has recently improved the SMP mandrel technology by adding a high-strain fiber reinforcement (HSFR) that both raises the toughness of the SMP and allows the SMP to elongate up to 150 percent. The resulting material can produce mandrels durable enough to withstand multiple use in high production rate manufacturing. This paper will demonstrate and discuss the feasibility of HSFR-SMP mandrels for filament winding and fiber placement and recent developments in CRG's SMP mandrel technology, including the fabrication of larger parts.

6171-21, Session 5

Metal rubberTM materials and devices

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This paper describes recent progress in the development of the Metal RubberTM family of nanocomposite materials, experimental evaluation of Metal RubberTM material and device properties, and envisioned engineering applications. Metal RubberTM is formed through the electrostatic self-assembly of multiple layers of electrically conducting nanoclusters and advanced polymers. A chemical release layer is first applied to a sacrificial substrate, the self-assembly process used to form material with desired thickness, and the release layer etched away to release the material from the substrate. Materials as thick as several millimeters and several feet square have been formed in this way. Electrical conductivities as high as 10-5 ohm cm and modulus from less than 1 MPa to greater than 500 MPa have been demonstrated. Typically such materials have been formed using gold nanoclusters; here early results with alternate lower cost materials including silver and copper are presented. This is interesting in that troublesome oxidation effects have been mitigated. Typically the thermal response of such materials has been limited; here early results indicating glass transition temperatures of -70C or lower and 5% weight loss temperatures of 350C or higher are presented. Electrical properties at high frequency, including S-, X- and K-band s-parameters in patterned 50 ohm waveguides, are also presented. Applications in electronics, aerospace and biomedical systems are suggested.

6171-22, Session 5

Adaptive wing structures: materials and design

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Aerospace systems stand to benefit significantly from the advancement of morphing structures technologies for active shape change of wings and aerodynamic surfaces. CRG is developing morphing structural systems supporting aerospace technologies through introduction of shape memory polymer as the seamless, adaptive skins for shape changing wings. Increased maneuverability and improved flight efficiencies over the entire flight profile result from the addition of these adaptive wing structures into future air vehicle systems. This paper outlines the progression and current status of the structures, materials, and systems technologies developed within CRG for the advancement of seamless, morphing structural systems.

6171-23, Session 5

Optimization of actuator- and sensor positions for an active noise reduction system

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In certain propeller driven military transport aircrafts the sound pressure level may reach up to 110 dB(A) caused by propeller blades producing disturbances when passing the fuselage in a certain blade pass frequency. This tonal noise appears in the low frequency range (up to 500 Hz). Different systems and strategies have been invented in order to reduce the noise level inside the fuselage. First of all passive methods like adding material with high damping or vibration absorbing qualities were used beside active noise reduction (ANR) systems. Due to mass reduction as a major aspect in aircraft design the research is focused on active noise reduction. ANR systems consist of actuators (speakers) and sensors (microphones) placed in a three dimensional space connected to a controller. Mostly a least square error method is implemented on a signal processor. One of the key elements in respect to the performance and efficiency of such a system is the positioning of the actuators and sensors.: The problem addressed in this paper is the noise reduction inside a semi closed loadmaster work station (LMWS) located in a propeller driven military transport aircraft. The maximum sound pressure level shall be lowered from 110 dB(A) to an acceptable noise level of 86 dB(A) due to work safety regulations and comfort. The frequencies taken into consideration are the blade pass frequency and its first two higher harmonics.: A hybrid evolutionary algorithm is introduced for the calculation of appropriate configurations for a fixed number of actuators and sensors out of a high amount of possible combina-

tions. This algorithm combines qualities of known optimization algorithm like the simulated annealing and genetic algorithms. Possible solutions/configurations are translated with a binary code into a string consisting of bits. The number of bits matches the number of possible actuator- and sensor positions. A population consists of a given number of individuals (possible solutions). After the reproduction of a descendant for every individual the phase of selection follows. A descendant is presented by a binary string which is the result of a recombination of two different strings belonging to individuals of the parental generation. The survival of either the parent or the direct descendant depends on the fitness, which will be determined by a cost function. This function weights the effort and the level of maximum noise reduction for each individual (combination of actuators and sensors). The algorithm ends after a certain amount of calculated circles consisting of different phases. The last generation contains possible solutions meeting the requirements. The advantages of this approach are saved calculation time and more than one reliable combination of actuator- and sensor positions, which can be evaluated in a mock up of the LMWS. For prospective applications this algorithm can be used for the positioning problem of ANR actuators and sensors.

6171-24, Session 5

Boeing's variable geometry Chevron: morphing aerostructures for jet noise reduction

F. T. Calkins, J. H. Mabe, G. W. Butler, The Boeing Co.

The paper will discuss the title subject.

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6172-01, Session 1

Army requirements for micro and nanotechnology-based sensors in weapons health and battlefield environmental monitoring applications

P. B. Ruffin, C. L. Brantley, E. Edwards, G. J. Hutcheson, U.S. Army Aviation and Missile Command; V. K. Varadan, Univ. of Arkansas

No abstract available

6172-02, Session 1

Evolutionary micro-accelerometer design synthesis

Y. Zhang, A. M. Agogino, C. H. Sequin, Univ. of California/Berkeley

An evolutionary microaccelerometer design synthesis process is introduced and demonstrated on the commercial product ADXL accelerometer family. The design synthesis process integrates a MEMS simulation tool with two levels of optimization: global genetic algorithms (GAs) and gradient-based local refinement.

Microaccelerometer design has multiple conflicting design goals: maximizing design sensitivity, minimizing noise floor, minimizing design area, achieving a target natural resonant frequency, and meeting structural requirements for minimum shocking survival acceleration, stiffness ratios, etc. To find the best designs which optimize and balance all the design performance criteria, a multi-objective genetic algorithm (MOGA) is used for the high level global optimization to handle multiple conflictive objectives and provide multiple design solutions on the Pareto optimal frontier. During the evolutionary synthesis process, MOGA works with an appropriate MEMS simulation tool during the iterative design synthesis process to generate the topology and dimensions of the microaccelerometer subject to the design constraints and performance objectives.

During the evolutionary microaccelerometer design synthesis process, a component-based chromosome representation is used. All the genes used to compose a chromosome are provided by an object-oriented component library. This chromosome representation incorporates knowledge specific to the microaccelerometer design problem into the chromosome representation. Each microaccelerometer design component is a gene, which has its own geometrical parameters. The common genes for a surface micromachined accelerometer includes mass plate, differential comb-drive, anchor, and various types of springs. A chromosome has multiple genes connected together based on their functionality. Each gene has control over its connectivity and encapsulates instructions and restrictions for genetic operations (crossover and mutation) during the evolutionary process. This representation provides a flexible mapping between genotype and phenotype, and the embedded constraints prevent the evolutionary process from spending too much time exploring the irrelevant regions of the design search space.

MOGA is a stochastically global search method. A large population size per generation is generally needed for the evolutionary process requiring a great deal of computation power and execution time to reach a near global optimum. Our previous studies of computational convergence show that GAs are best suited for conceptual design in deriving the general shape and topology, but are inefficient for fine tuning around a potentially good solution. A conventional gradient-based optimization algorithm is used to further refine the selected microaccelerometer designs at the end of the evolutionary synthesis process at less computational expense.

A microaccelerometer with performance requirement similar to the commercial ADXL150 product is used to test the evolutionary synthesis process with different design constraints. Since MOGA can provide multiple design solutions on the Pareto optimal frontier, the best design tradeoff across multiple design objectives is explored based on the final solutions. A fast MEMS simulation tool (SUGAR) based on the modified nodal analysis and some simplified performance evaluating models are used to evaluate the performances of microaccelerometer during the evolutionary synthesis process. The final selected designs are analyzed using finite element analysis to more accurately predict the final design performance.

6172-03, Session 1

Frequency tuning of film bulk acoustic resonators

A. A. Frederick, W. W. Clark, H. Hu, Univ. of Pittsburgh

This paper suggests a design for a Film Bulk Acoustic Resonator (FBAR) which utilizes a secondary piezoelectric layer for purposes of tuning the FBAR's resonant frequency.

Currently, ceramic resonators and SAW resonators have difficulties in on-chip integration, power handling capability and electrode fabrication. FBARs are not only simple to fabricate and capable of full integration with CMOS/RF IC circuitry, but they are also highly compact and can achieve high frequencies (in the GHz) with high quality factors. Such benefits are becoming increasingly important for applications where overall system miniaturization, component combination and high power handling are judged to be more and more necessary.

Despite the many benefits offered by FBARs, difficulties have existed in matching their resonant frequencies to specified values or adjusting these frequencies to be stable during temperature variations. Consequently, a design that would allow the frequency of the device to be passively or actively tuned in order to compensate for these shortcomings could offer many benefits in the usability of FBARs.

It is widely accepted that piezoelectric actuators encounter a significant change in mechanical stiffness between their open-circuit and closed-circuit states. In addition, it has been previously shown that the resonant frequency of a multi-layer FBAR is a function of the acoustic impedances and, correspondingly, the acoustic velocities, of its respective layers. Since the stiffness term of the acoustic velocity of an FBAR layer is dependant upon both the mechanical properties and electromechanical coupling of its piezoelectric element, the stiffness of the piezoelectric tuning layer can be adjusted in such a way as to vary the resonant frequency of the device. The maximum stiffness will result from the short-circuit conditions, the minimum stiffness will result from the open-circuit conditions, and the effective stiffness can be varied between these values by inserting shunt capacitors in parallel with the piezoelectric tuning element. The effects which different materials and different thickness dimensions for the FBAR layers have on the frequency range and degree of tunability of the device are also investigated in this work.

6172-04, Session 1

Passive wireless sensor modeling with RFID

J. K. Abraham, A. K. Whitchurch, V. K. Varadan, Univ. of Arkansas

No abstract available

6172-05, Session 2

Carbon nanotube array smart materials

Y. Yun, V. N. Shanov, M. J. Schulz, Univ. of Cincinnati; Y. Tu, First Nano, Inc.; S. Yarmolenko, S. Neralla, North Carolina A&T State Univ.

Highly aligned multi-wall carbon nanotubes up to 4 mm in length were synthesized on Si wafers. The effects of substrate preparation and water assistance were studied to understand the nature of CNT growth. Based on mm long nanotube carpets, several prototype smart materials were developed including a biosensor, force actuator, and a nanoskin. The biosensor was formed by casting epoxy into the nanotube array and polishing the ends of the nanotubes. This electrode produced a near ideal sigmoidal cyclic voltammogram. Electrochemical actuation of the as-grown nanotube array was demonstrated in a 2 M NaCl solution. The CNT array force actuator is 1mm square by 4 mm long and actuates up to 10 Hz. A driving voltage of 2 volts produces 0.2% strain. Electrochemical impedance spectroscopy and potential step chronocoulogram analyses were carried out to characterize the electrochemical properties of the nanotube tower actuators. Finally, different types of nanoskins were formed using the arrays. Wetting studies showed that the nanoskin can have a super-hydrophobic property and this property can be tuned by changing the patterning of the nanotube array. A more hydrophilic surface was also produced through functionalization of the nanotube array. Overall, the nanotube array represents a new smart material with multifunctional properties that can be tailored for many potential applications.

6172-06, Session 2

Biomolecules as nanomaterials: interface characterization for sensor development

G. R. Goddard, J. E. Whittier, Los Alamos National Lab.

Extensive research is underway to understand and exploit the interface between biological materials and integrated systems. Knowledge of these interfaces is critical for a wide range of emerging biomedical technogies. Techniques developed originally in the context of semiconductor microelectronics and organic synthesis have been employed to assemble DNA-based nanoscale machinery. Biosensors, such as those based on electron transfer between an electrode and a redox enzyme, and bio-photodiodes based on fluorescent proteins and inspired by the electron transport cascades in natural photosynthesis represent some of the more promising advances in this area. All of these systems involve tailoring and manipulating the boundaries between biomolecules and artificial surfaces. Against this general background, we will present our work on the use of fluorescence correlation spectroscopy to determine characteristics of the molecular surface, and impedance spectroscopy to electrically deconvolve the various components of the signals during binding interactions. This allows us to elucidate the nature of the interface between biomolecules and sensor platforms and subsequently to demonstrate the benefits of this technique for studying molecular interactions. We will describe issues associated with: the incorporation of biomolecules into a sensor platform, and the application of this system to studying the interactions between biomolecules and a microtubule substrate.

6172-08, Session 2

Carbon nanotube/polymer array for photovoltaic applications

J. Xie, V. K. Varadan, Univ. of Arkansas

No abstract available

6172-09, Session 2

Novel materials for organic thin film-based sensors and electronics: a review

T. Ji, J. Xie, V. K. Varadan, Univ. of Arkansas

No abstract available

6172-10, Session 3

Ultrasonication of bismuth telluride nanocrystals

S. Chu, S. H. Choi, J. Kim, Y. Park, G. C. King, P. T. Lillehei, J. R. Elliot, NASA Langley Research Ctr.

The objective of this study is to evaluate the effect of ultrasonication on bismuth telluride nanocrystals prepared by solvothermal method. A thermoelectric (TE) material of high figure of merit should have high electrical conductivity (σ) and low thermal conductivity (k), which is represented by the concept of "phonon-glass/electron-crystal." Low-dimensional nanocrystals and superlattice thin films ensure strong phonon scattering to induce low thermal conductivities, while skutterudites and clathrate crystals are typical TE materials which exhibit the crystalline nature that yield good electric properties. In this study, a low dimensional nanocrystal of bismuth telluride (Bi2Te3) was synthesized by a solvothermal process in an autoclave at 180°C and 200 psi. During the solvothermal reaction, organic stabilizers such as ethylenediaminetetraacetic acid (EDTA) or cetyltrimethylammonium bromide (CTAB) effectively prevented unwanted aggregation of nanocrystals in a selected solvent while controlling the shape of the nanocrystal. The atomic ratio of bismuth and tellurium was determined by energy dispersive spectroscopy (EDS). The dimensional characteristics of nanocrystalline bismuth telluride were modified by a subsequent ultrasonication process. The cavitational energy created by the ultrasonic probe was varied by the process duration and power amplitude, respectively. The nanocrystal size and its size distribution were measured by scanning electron microscopy (SEM), atomic force microscopy (AFM) and particle size analyzer, which showed that the average size and polydispersity of the nanocrystals were decreased with increasing cavitational energy. The parametric study of ultrasonication suggested an optimal processing window for complete dispersion and size control of the bismuth telluride nanocrystals.

6172-11, Session 3

Hydrogen production using a nanostructured electrolyzer

S. Kim, N. A. Koratkar, T. Karabacak, T. Lu, Rensselaer Polytechnic Institute

Hydrogen production and delivery is critical to successful fuel cell operation. One of the most convenient methods to produce hydrogen is via electrolysis of water. However over-potential losses at the electrodes results in poor efficiency and increase in power consumption. In this paper we present a novel water electrolyzer cell featuring Ruthenium nano-rods as the device cathode. We show that the increased surface area associated with the nano-rod electrode results in up to 25% reduction in the over-potential loss at the cathode. The increased active area of the electrode serves to reduce the current density causing the activation over-potential to decrease. In addition to the decrease in the activation over-potential, the power needed to produce one mole of Hydrogen was also reduced by about 15% for the nanostructured electrolyzer compared to an electrolyzer with planar electrodes.

We also varied the length of the Ruthenium nanostructures that comprise the device cathode. Weak dependence of the nanostructure length on performance was observed. This was because the packing density of the Ruthenium nanostructures was too large and hence only the sharp tip regions of the nanostructures was found to play an active role in the electrolysis reaction. The side walls of the nanostructures were not being exposed to water due to the high packing density of the nanostructures. For this reason increasing the length of the nano-rods (i.e. increasing the length of the side walls) did not have a significant impact on the over-potential losses.

Future work will focus on controlling the nanostructure-to-nanostructure spacing to ensure that the entire surface of the nanostructure will participate in the electrolysis process. Also carefully designed experiments are planned to quantify the ohmic losses for both a planar electrode as well as for a nanostructured electrode geometry.

6172-12, Session 3

Novel dielectrophoretic filtration methods and designs

B. Y. Park, M. J. Madou, Univ. of California/Irvine

Researchers estimate that 80% of all machine failures are due to wear [1] and that 1.3~1.6% of an industrialized nation¡¯s GNP is lost to degradation of machinery due to friction-related wear [2]. The abnormal abrasive wear due to lubricant contamination in marine diesel engines eclipses that of normal wear (wear that occurs even without abrasion) and the gap becomes wider with time [3]. It was found that although oil filters used in automotive engines are designed to filter particles in the 15-30 µm range, particles with diameters below 10 µm caused 44% of the wear to engine cylinders [4]. We believe that dielectrophoretic forces can be used to remove small (<10µm) particles while providing on-line monitoring of oil contamination.

Traditional methods of dielectrophoretic separation using planar microelectrodes have a common problem: the dielectrophoretic force, which is proportional to , rapidly decays as the distance from the electrodes increases. In this contribution, the use of 3D electrode designs for high-throughput dielectrophoretic separation/concentration/filtration systems is investigated. 3D electrode designs are beneficial because 1) They provide a method of extending the electric field within the fluid. 2) The 3D electrodes can be designed so that the velocity field coincides with the electric field distribution. 3) Novel electrode designs, not based on planar electrodes designs, can be developed and used. The electric field distribution and velocity fields of 3D electrode designs that are simple extensions of 2D designs are presented, and three novel electrode designs that are not based on 2D electrode designs are introduced.

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6172-13, Session 3

Fabrication of carbon MEMS electrodes with carbon nanofibers for lithium ion microbatteries

R. Zaouk, C. Wang, M. J. Madou, Univ. of California/Irvine; V. K. Kayastha, Y. K. Yap, Michigan Technological Univ.

Carbon MEMS is a growing field of research that has attracted some interest recently because of its possible applications in the field of electrochemistry,

microbattery fabrication, dielectrophoretic colloid sorting, DNA arrays, etc. Carbon MEMS results from the pyrolysis of photoresist (e.g. SU-8) in an inert or reducing environment. In this paper we describe for the first time, the process in which we can get carbon MEMS structures that have inherent nanotexture features.

We describe how carbon nanofibers (CNF) can be obtained on the surface of the carbon microstructures during the pyrolysis step that is normally used to transform the photoresist from polymer to quasi glassy carbon [1-3]. Several methods achieving that purpose will be described: premixed MWCNT and photoresist, premixed catalyst and photoresist, catalytic thermal chemical vapor deposition.

The elegance of the carbon MEMS microstructures with CNF is that they provide a direct access between the micro and the nano world because both structures and fibers are formed in the same processing step. The usual method that is traditionally utilized consists of growing carbon nanofibres or nanotubes and then building a system (usually transistor or other) around the places where the nanofibers grew. In the proposed fabrication process, the photoresist is premixed with nanofibers or catalyst or seed nanoparticles that allow simultaneous photopatterning of conductive carbon microstructures and the direct integration of carbon fibers at the surface of these microstrucutures.

Growing CNF on C-MEMS high aspect ratio electrodes increases the surface area of such electrodes and makes them more suitable for applications such as microbattery electrodes [3].

The process of building both the contacts and growing the carbon nanofibers in the same step is very important because it allows the fabrication of easily addressable chemical and biological sensors using carbon nanofibers.

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6172-14, Session 3

Nickel electrodeposition studies for high-aspect-ratio microstructure fabrication for MEMS

T. Xin, P. K. Ajmera, Louisiana State Univ.

High-aspect-ratio microstructures offer many performance advantages and are desirable for many MEMS. Electroplated nickel is a commonly employed material for microstructure fabrication. This work investigates both DC and pulse electroplating techniques for nickel. A nickel sulfamate electrolyte is utilized for nickel deposition over Cu/Ti coated silicon substrates. Stress levels, grain sizes and microstructure height uniformity are investigated here for the electroplated nickel. A comparison is made between the results obtained from DC and from pulse electroplating techniques.

For the DC plating case, it is found that the internal stress in nickel deposit changes from compressive to tensile as cathodic current density is increased. The value of stress saturates when the current density is over 30 mA/cm2. Shifts in nickel lattice constant obtained from X-Ray diffraction measurement are used to determine stress. For DC plating, the stress transition from compressive to tensile also occurs with increasing thickness of nickel deposits and saturates for thicknesses over 10 um.

For pulse plating with long duration on-pulses of 10 s, it is found that the nickel deposits undergo transformation from compressive stress to tensile stress as pulse off time increases from 0.5 to 3 s. The stress value saturates as pulse off time increases from 3 s to 20 s. A comparison between the saturated stress values given by DC and long on-pulse electroplating cases under otherwise similar conditions shows that the stress value in the pulse plated deposits is about 1/3 that of the value observed in the DC plated deposits. It is also observed that pulse plating circumvents the diffusion layer problem that plagues DC plating through deep recesses present in high-aspect-ratio microstructure plating molds. Pulse plating by short on-pulses in ms range were found to always give compressive built-in stress.

A transient model is presented here for pulse plating. Experimental results on electroplating a microprobe array structure with varying dimensions are compared to the results predicted by the model. Analysis and comparisons on grain size and morphology are made by varying the pulse on time and the pulse off time for the long and the short pulse electroplating cases. Pulse plating technique yields the microprobe array with more uniform height compared to the DC plating case as the double layer discharging current avoids non-uniform ohmic drop in the recess molds in the latter case.

6172-15, Session 3

Micro-patterning on cellulose electro-active paper for biodegradable MEMS

S. H. Bae, J. Kim, S. Yun, Inha Univ. (South Korea)

With technological interests in renewable raw materials and more environmentally friendly and sustainable resources, a renaissance of cellulose research and application has been triggered over the past ten years. We report a discovery of cellulose paper as smart material that can be used for bio-mimetic sensor/actuator devices and microelectro-mechanical systems. This cellulose paper is termed as Electro-Active paper (EAPap). Since cellulose EAPap material is ultra-lightweight, dry, cheap, low actuation voltage, low power consumption and biodegradable, it can be useful for many applications such as micro insect robots, micro flying objects, microelectro-mechanical systems, biosensors and flexible electrical displays.

The proposed idea is based on the Electro-Active cellulose paper (EAPap) that will offer adaptation of MEMS technology with the biodegradable paper and the capability of sensor and actuator functions on it. Key issues in this biodegradable MEMS fabrication with EAPap are 1) the preparation of EAPap material for micro scale fabrication, 2) micro patterning possibility on EAPap and 3) functional capabilities of sensing and actuation. This paper will introduce a micro contact printing for the micro patterning process on the EAPap flexible membrane. And the EAPap material preparation and the test of multi-functional capabilities of sensing and actuation will be addressed.

6172-16, Session 3

Science and art of synthesis and crafting of nano/microstructures and devices using ion-crafted templates: a review

S. K. Chakarvarti, National Institute of Technology/Kurukshetra (India)

Nano/Microstructures consisting of either metallic nano/microdimensional devices, fibrils, needles or tubules have attracted attention for their potential applications in multidisciplinary areas including microelectromechanics, field-emission electrodes, conductive polymers, Resonant Tunneling Devices(RTDs), transparent metal structures,mimicking bio-tubules etc.As the size of the materials or devices shrink down to very low-dimensional geometries and configuration, various interesting and important quantum phenomena start occuring. This therefore calls for devicing apporopriate techniques and strategies for synthesis and crafting of such materials and devices as above.In the presentation, recently matured, versatile and easy-to-handle technique of Template Synthesis using particle track-etch membranes as templates would be reviewed highlighting various its aspects and applications. Some of the results obtained in our laboratory would also be discussed.

6172-17, Session 4

Aligned nanowire structures on silicon and flexible substrates and their applications

C. Langton, H. Yoon, V. K. Varadan, Univ. of Arkansas; P. B. Ruffin, U.S. Army Aviation and Missile Command

No abstract available

6172-18, Session 4

Development of a nanowire array for wireless neural probe

J. K. Abraham, J. Xie, S. Komarneni, V. K. Varadan, Univ. of Arkansas

No abstract available

6172-19, Session 4

Magnetic nanostructures and drug delivery systems

L. F. Chen, V. K. Varadan, Univ. of Arkansas

No abstract available

6172-20, Session 5

Lifetime characterization of capacitive power RF MEMS switches

A. Ziaei, T. Dean, Thales Research & Technology (France)

RF MEMS switches provide a low-cost, high performance solution to many RF/

microwave applications and these switches will be important building blocks for designing phase shifters, switched filters and reflector array antennas for military and commercial markets.

In this paper, progress in characterizing of THALES capacitive MEMS devices under high RF power is presented. The design, fabrication and testing of capacitive RF MEMS switches for microwave/mm- wave applications on high-resistivity silicon substrate is presented.The switches tested demonstrated power handling capabilities of 1W (30 dbm) for continuous RF power. The reliability of these switches was tested at various power levels indicating that under continuous RF power. In addition a description of the power failures and their associated operating conditions is presented.

The PC-based test stations to cycle switches and measure lifetime under DC and RF loads have been developed. Best-case lifetimes of 1010 cycles have been achieved in several switches from different lots under 30 dbm RF power.

6172-21, Session 5

RF MEMS separable electrical connector

M. P. Larsson, Imperial College London (United Kingdom)

A two-part, separable RF MEMS electrical connector is demonstrated in low resistivity silicon (LRS) using thick SU-8 to reduce coupling between transmission lines and the lossy silicon (Si) substrate. Fabrication involves a combination of deep reactive ion etching (DRIE) and anisotropic wet etching in potassium hydroxide (KOH) solution. The latter conveniently forms features in connector halves that enable precise lateral and vertical self-alignment during mating. Connector pins deflect perpendicular to the substrate plane upon connection, with high force elastic contacts made possible through the presence of supporting Si cantilevers. A major challenge in the fabrication of working prototypes was the need to prevent peeling of SU-8 strips during immersion in KOH. This led to the development of a technique to augment SU-8 adhesion to Si using micro-mechanical interlocking.

Micromachined transmission lines have been realised in both low- and high-resistivity Si substrates. In the latter, the high resistivity of the substrate minimises capacitive coupling which degrades high-frequency signals. A disadvantage of HRS, however, is its limited compatibility with CMOS processes and subsequent difficulties of integration with microelectronic circuitry. By raising transmission lines from the Si substrate through the use of thick photopolymer layers such as polyimide, benzocyclobutene (BCB) and SU-8, LRS substrates can be viable for RF devices. Given the proliferation of micromachined transmission lines providing access to solid state components, it is likely that there will be a requirement for miniature, high-speed interconnects to link discrete modules within future microsystems. This work presents the first realisation of a MEMS separable connector for high-frequency applications.

Key fabrication steps for connector halves are as follows: First, a thermally oxidised, double-side polished BSOI wafer (75 um top-layer with (100) orientation) is patterned and etched on the back-side through DRIE to form vertical cavities extending to the buried oxide. The front-side is patterned to define openings for isotropic DRIE to form pits with overhanging sidewalls. Following re-oxidation, the front-side oxide is again patterned, defining masking regions for Si cantilever formation through anisotropic KOH etching at a later stage. SU-8 is applied to the pitted substrate and spun to a thickness of 20 um above the top surface. Signal-ground transmission lines are subsequently electroplated in Cu, to a thickness of 3 um, with a 1 um cobalt-gold (Co-Au) surface layer. The latter is an Au alloy which, in addition to ensuring oxide-free contacts, offers improved abrasion resistance over pure Au. The final step involves immersion in 40% KOH solution at 80 deg C to etch the front-side to the buried oxide, completing the formation of compliant Si/SU-8/conductor connector pins and passive alignment features.

Electrical characterisation on multi-pin prototypes reveal low and consistent contact resistance between conductors on adjacent pins. An average contact resistance of 44 mOhms is measured on contacting signal lines in one assembly. Atomic force microscopy on the conductor surface reveals a low surface average roughness (Ra) of 905 Å. Key RF performance parameters, including insertion loss, return loss and signal rise time, will be presented.

6172-22, Session 5

Micromachined piezoelectric resonator at MHz application

T. T. Le, Philips Semiconductors (France); L. Valbin, Groupe ESIEE (France); F. Verjus, Philips Semiconductors (France); T. Bourouina, Groupe ESIEE (France)

Since few years, the MEMS technology for microwave applications has grown up with the potential to improve the circuit and device performances. Several components have been designed and demonstrate an important reduction of loss and a higher linearity than their main counterparts: the semi-conductor components. Currently, we can distinguish several categories of components and circuits resulting from this technology, for example: micro-switches, variable capacitances, and circuits on dielectric diaphragms, micro-machined inductances and resonators. Very compact and high-performance, these devices have a strong potential. They form a new generation of radio frequencies components (RF) that will make it possible to increase the performances of the circuits in which they will be integrated. This work investigates the Thin Film Bulk Acoustic Resonator (TFBAR) operating at low frequencies. The purpose of this study is to substitute quartz resonators in the 4-27 MHz band and to achieve selective filter for frequencies lower than 1GHz with quality factor higher than 100 within Philips. TFBAR has advantages of small size, low power, low insertion loss, band pass filter with high frequency, and good bandwidth.

The commonly available thin film piezoelectric materials for BAW devices are aluminium nitride (AlN) and zinc oxide (ZnO). AlN, especially, does not have a metal, which performs the recombination centre of the carriers such as zinc of ZnO. Hence, AlN is attractive for the CMOS integration and moreover it is an excellent material for small to medium bandwidth filters (bandwidth <5%). In addition, AlN film has several other advantages such as high breakdown voltages and low dielectric loss.

In this paper, we address the design, fabrication and testing of two different types of micro machined piezoelectric bulk acoustic resonator. They consist of an AlN film (0.8 μm) sandwiched between two Al electrodes (0.2 μm each) on a silicon substrate. The first resonator is made by clamped edge beam and the second one is a free-free beam construction anchored in the middle of the cantilever. A demonstrator was achieved and the resonators are fabricated on a silicon (Si) substrate; AlN and Al layers were deposited on silicon using standard cathode sputtering technique.

The resonators operate in extensional mode and the thicknesses of each material are lower than 1μm. ANSYS, a Finite Element Analysis (FEA), has been performed to simulate the static, modal and harmonic behaviour. The simulation has been used firstly, to determine the thicknesses of each material for obtaining the desired frequency range and secondly, to compare between theoretical and experimental frequencies values. First resonant frequencies between 1 and 39MHz were measured for resonators with dimensions of 20-200μm wide and 50-1000μm long and are close to theory. Quality factor under 10000 operating in air has been obtained.

6172-23, Session 5

Design and applications of flexible dipole rectenna for smart actuators and devices

K. D. Song, W. T. Golembiewski, S. Jones, Norfolk State Univ.; S. Yang, J. Kim, Inha Univ. (South Korea); S. H. Choi, NASA Langley Research Ctr.

There are several potential candidates for energy harvesting technologies suitable for smart actuators and devices, such as space vehicles, high altitude airships, MAVs (Micro-Aero Vehicles), and smart robots. Smart material actuators have actively been developed in previous decades in order to control shape changes or actuate proper devices, but their applications as a practical system are limited due to the requirements of hard-wire circuits and high voltage. These limiting factors have been key challenges to overcome for practical applications of smart materials. The hard-wire circuits are inappropriate for power feed and control of smart materials actuators for MAVs and space vehicles applications. In addition, the hard wiring may not be a suitable solution due to the network complexity. Moreover, the weight increase may be attributed to the a wired network, the complex gate switching of power and control networks needed, and the interdependency of power and control routines needed.

Flexible dipole rectenna devices appeared to be attractive for various applications because of the adaptability on complex structures; possibility for higher power density features, and ability of coupling. In this study, design concepts and test results of various flexible dipole rectennas will be discussed. Using the results, the system level applications of the flexible dipole rectenna array will also be addressed.

6172-24, Session 5

Design of the parallel packet switch architecture

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Our work is motivated by the desire to design packet switches with large aggregate capacity and fast line rates. In this paper, we consider building a packet switch from multiple lower speed packet switches operating independently and in parallel. In particular, we consider a (perhaps obvious) parallel packet switch (PPS) architecture in which arriving traffic is demultiplexed over k identical lower speed packet switches, switched to the correct output port, then recombined (multi-

plexed) before departing from the system. Essentially, the packet switch performs packet-by-packet load balancing, or inverse multiplexing, over multiple independent packet switches. Each lower speed packet switch operates at a fraction of the line rate R. For example, each packet switch can operate at rate R/k. It is a goal of our work that all memory buffers in the PPS run slower than the line rate. Ideally, a PPS would share the benefits of an output-queued switch, i.e., the delay of individual packets could be precisely controlled, allowing the provision of guaranteed qualities of service.

In this paper, we ask the question: Is it possible for a PPS to precisely emulate the behavior of an output-queued packet switch with the same capacity and with the same number of ports? We show that it is theoretically possible for a PPS to emulate a first-come first-served (FCFS) output-queued (OQ) packet switch if each lower speed packet switch operates at a rate of approximately 2R/k. We further show that it is theoretically possible for a PPS to emulate a wide variety of quality-of-service queueing disciplines if each lower speed packet switch operates at a rate of approximately 3R/k. It turns out that these results are impractical because of high communication complexity, but a practical high-performance PPS can be designed if we slightly relax our original goal and allow a small fixed-size coordination buffer running at the line rate in both the demultiplexer and the multiplexer. We determine the size of this buffer and show that it can eliminate the need for a centralized scheduling algorithm, allowing a full distributed implementation with low computational and communication complexity. Furthermore, we show that if the lower speed packet switch operates at a rate of R/k (i.e., without speedup), the resulting PPS can emulate an FCFS-OQ switch within a delay bound.

6172-25, Session 6

High-frequency SAW oscillator sensor to measure DNA immobilization and hybridization

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We developed SH (shear horizontal) surface acoustic wave (SAW) sensors for detection of the immobilization and hybrdization of DNA (deoxyribonucleic acid) on the gold coated delay line of transverse SAW devices. The experiments of DNA immobilization and hybridization were performed with 15-mer oligonucleotides (probe and complementary target DNA). The sensor consists of twin SAW delay line oscillators (sensing channel and reference channel) fabricated on 36° rotated Y-cut X-propagation LiTaO3 piezoelectric single crystals. The relative change in the frequency of the two oscillators was monitored to detect the immobilization of probe DNA with thiol group on the Au coated delay line and the hybridization between target DNA and immobilized probe DNA in pH 7.4 PBS (phosphate buffered saline) solution. We reported the sensitivity of 1.26 ng/ml/Hz of 100 MHz SAW sensors. Sensitivity of the SAW sensor is in nonlinear proportion to the oscillation frequency of the SAW device. Significant improvement of the sensitivity of the SAW DNA sensor has been achieved by increasing the oscillation frequency to 200 and 300 MHz in sequence. The sensitivity of the 200 MHz sensor was improved to as high as 156 pg/ml/Hz and that of 300 MHz sensor as high as 55 pg/ml/Hz. We addressed many engineering problems required for the increase of the oscillation frequency such as electromagnetic noise isolation, mechanical vibration isolation, acoustic noise absorbing, and digital signal processing. Normally, it is considered that a SAW sensor is inferior in sensitivity to optical systems. However, the results in this paper confirm the promising practical applicability of the SAW sensor. Comparison of the SAW sensor performance with that of competing technologies is discussed.

6172-26, Session 6

Multi-functional surface acoustic wave sensor for monitoring enviromental and structural condition

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Safety evaluation and security control become most important in the complicated IT (information technology) society and human life, therefore, the combination between the multi-functional sensor/actuator devices and telecommunication module will undoubtedly extend toward more wide application fields of intelligent/smart materials and structures. In this study, as a first step toward health monitoring system with active and embedded nondestructive evaluation module etc., wireless sensing and active sensing for smarter design concept of machinery and structures, a multi-functional SAW (surface acoustic wave) device was developed and its dependency on environmental parameters such as temperature , stress/strain and cyclic loadings etc. was investigated. (see Fig.1)

In the experiment, two piezoelectric quartz (st-cut) and LiNb3(x-y cut) base materials were used. IDT(30mm length and 20μm pitch) was produced by lithography. The sensor and experimental set-up for temperature stress sensing etc.. On the surface part between IDTs, environmentally active material films were sputtered by magnetron-sputtering technique. In this study, two kinds of shape memory alloys(SMA) system were formed to measure 1) stress-strain hysteresis under cyclic loading and 2) loading level and 3) phase transformation for loading number evaluation because of their linearity and non-linearity for cyclic stressing. Temperature and stress dependencies of SAW signal were also investigated in the non-sputtered film state. The measuring acoustic wave parameters of signal amplitude and phase change were chosen to measure as the sensing parameters. As a result, temperatuere, stress and phase transformation in SMA depending temperature could be measured by the proposed multi-functional SAW.

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6172-27, Session 6

Sensor- integrated polymer actuators for closed-loop drug delivery system

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This work presents manufacturing and testing of a closed-loop drug delivery system where drug release is achieved by an electrochemical actuation of an array of polymeric valves on a set of drug reservoirs. The valves are based on bi-layer structures made of polypyrrole/gold in the shape of a flap that is hinged on one side of a valve seat. Drugs stored in the underlying chambers are released by bending the bi-layer flaps back with a small applied bias. These polymeric valves simultaneously function as both drug release components and biological/chemical sensors responding to a specific biological or environmental stimulus. The sensor array sends signals to the control module to realize closed-loop control of the drug release. In this study a glucose sensor has been integrated with the polymeric actuators through immobilization of glucose oxidase (GOD) within polypyrrole valves. Insulin is pre-stored in an array of drug chambers; the amount of released insulin is precisely controlled by the surrounding glucose concentration detected by the glucose sensor. A specific controlling algorithm and signal processing techniques are implemented inside the control module which connects the sensor and the actuator components. An energy budget of the whole system is also discussed. Backup glucose sensors are installed inside the separate chambers and activated by an opening of the valve in response to a glucose sensor failure due to causes such as tissue response that dramatically decreases the lifetime of the most conventional glucose sensors in in-vivo environment. An array of chambers that can release various therapeutic agents is added for versatility. Activation of these reservoirs can be triggered either by the signal from the sensor, or by the signal from the operator. This approach also serves as the initial step to use the proposed system as an implantable drug delivery platform in the future.

6172-28, Session 6

Neuroelectronics and neurosurgery

V. K. Varadan, Univ. of Arkansas

No abstract available

6172-29, Session 7

Application of probe manipulator to repair probe cards

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We fabricated an apparatus for manipulation and welding of fine metal objects using a probe. We investigated on the application of the apparatus to the electronic industry. One of the applications is to repair probe cards. The apparatus is composed of a work probe, stages, a DC power source, and an observation system. A tungsten needle (660 micrometers in diameter) is used for a work probe. It is held vertically above a gold substrate (10mm x 10mm) placed on the stages to control the relative position against the work probe. The DC power source is equipped to apply voltage between the work probe and the substrate. The output is adjustable wide ranges from 0 to 10kV at a step of 10V. The maximum power rating is 10kV x 1mA. Two stereomicroscopes are focused on the tip of the work probe from horizontal orthogonal directions. The operator can monitor the tip of the work probe through CCD cameras attached to the stereomicroscopes. Probe cards are a tool to test IC chips on the wafer. Thousands of probe needles are mounted on one side of the probe card. It is put on a wafer to make electrical contact with IC chips fixed on the wafer. Each needle is in contact with each bonding pad to check electrical signals of the IC chips. The probe needles are

placed one by one by the hands. Recently probe cards are produced by the LIGA process in response to narrower semiconductor pitch length. The problem of such MEMS probe is that there are no methods to repair bad probe needles. Whole of a probe card should be a waste owing to one bad probe needle. We try to replace a bad probe needle with a good one using our apparatus. The sample of MEMS probe is supplied from Japan Electronic Materials Corporation. The probe needle is a cantilever type and is arranged with a pitch of 25 micrometers. Removal is carried out as follows. The substrate of MEMS probe is put on the work table, and the work probe is moved just above the root of a probe needle. The distance is adjusted to about 20 micrometers. Applying 10kV to the work probe, the root is cut by the discharge within 5 seconds. The probe needle cut off is attracted to the tip of the work probe by the electrostatic force. As the work probe holds the probe needle by adhesions, the probe needle can be carried off by the work probe. We have not carried out to mount a new probe needle yet. New probe needle will be manipulated and welded by this apparatus similar to the metal particles. Gold particles and nickel particles are manipulated and welded by the apparatus. The particles are adhered at the tip of the work probe by applying 40-60V. After the particles are placed, 10kV is applied. Then, the particle is welded.

6172-30, Session 7

Self-assembled polymer MEMS sensors and actuators

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This paper describes the design, fabrication and operation of polymer MEMS (PMEMS) sensors and actuators through the molecular self-assembly of metal and metal oxide nanoclusters in combination with advanced polymers. Self-assembly has been used for many years to form ultrathin films, typically on the order of hundreds of nanometers thick, on substrate surfaces. Recent work has demonstrated the ability to scale this process to the formation of materials several microns to several millimeters in thickness, and to form free-standing films of such materials by first applying a chemical release layer to the substrate and then etching away the release layer once a film of the desired thickness is formed. Additional recent work has demonstrated the ability to spatially pattern the surface of self-assembled materials using selected surfactants. Here we report new work in the development of patterned and interconnected PMEMS sensors and actuators inspired by these processes. By controlling the materials self-assembled into the film materials, a range of different constitutive behaviors may be realized, including electrical conductivity, permittivity, permeability and modulus, and these behaviors allow the patterning and formation of electrical devices such as resistors, capacitors, inductors, conducting interconnects and piezoelectric materials. In some cases, changes in the materials used to form these devices at the molecular level occur due to external stimuli, and in these cases, transducers may be realized. We report two examples of such PMEMS transducers here, specifically strain sensor elements and chemical concentration sensor elements based on chemically designed and patterned elements.

6172-31, Session 7

Photonic crystal sensor systems for sub-micron damage detection, quantification, and diagnoses

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Photonic crystals (PC) are artificially fabricated crystals with a periodicity in the dielectric function. These crystals have the novel ability to mold and control light in three dimensions by opening a frequency region (bandgap) in which light is forbidden to propagate. If fabricated from non-dispersive materials, the frequency response of these crystals is linear in the periodicity length of the dielectric function. The photonic band structure results when light encounters a well-defined repeating arrangement of materials with differing refractive indexes. When correctly designed and fabricated, such structures can exhibit the property that photons with the band gap energy can not penetrate the lattice regardless of their angle of incidence.

The arising photonic band gap is inherently tied to the underlying photonic lattice topology, periodicity, and integrity. As such the spectral response of these photonic lattices is very sensitive to geometrical variations due to strain induced from microdamage. We thus propose using photonic crystals as sensors fabricated at the micron length scale to detect sub-micron damage in composite materials. We demonstrate using a simulation model that a photonic crystal sensor attached to a composite substrate will experience a significant change in its bandgap profile when damage is induced in the composite substrate. The model predicts the frequency response of the photonic crystal sensor using the finite difference time domain (FDTD) method. A damage metric using principles of fuzzy pattern recognition is developed to evaluate and quantify the change in the frequency response in relation to the induced damage. Results for different damage scenarios are examined and reported with significantly high success rate. Successful developments of photonic crystal sensors will allow damage identification at scales not attainable using current sensing technologies.

6172-32, Session 7

Self-assembled nanostructured multilayer spectral filters

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This paper describes recent progress in the development of multilayer dielectric stack optical spectral filters using electrostatic self-assembly processes. Molecular self-assembly has been used for many years to synthesize ultrathin film nanocomposite coatings on substrate materials. Typically such self-assembled nanocomposites have been on the order of one or several hundred nanometers in thickness, so unsuitable for use as spectral filters that may require thicknesses of several optical wavelengths, so several microns. Recent improvements in self-assembly have led to faster processing times and better control over material properties. Multilayer dielectric stack optical filters require the deposition of multiple layers of material with controlled thicknesses and relative permittivities. Here we report how self-assembly can be used to form such materials. Specifically, we report the combination of advanced polymers and selected and synthesized oxide nanoclusters to form filter segments of controlled relative permittivity. We cite processing limits on both the control of thickness and permittivity, and show how these limits affect systems-level filter performance metrics such as 3-dB bandwidth and sidelobe suppression. Generic filter designs and corresponding experimental measurements of fabricated devices are reported.

6172-33, Session 7

FBG read-out system based on a silicon-based Fabry-Perot cavity

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In the last years, there has been a considerable interest in the development of fibre optic sensor based on in-Fibre Bragg Gratings (FBGs). Their small dimensions, the immunity to EMI, the absence of electrical signals and cables, their capability to be embedded or attached to different materials without perturb the material itself, as well as the protection from various environments by way of the optical fibre coating, renders them the ideal sensors for structural health monitoring or the design of “smart structures”. Moreover, in a FBG the information signal is “wavelength encoded”, meaning that a physical parameter variation produces a wavelength shift in the spectral response of the sensor. Thanks to these features, today it is very easy to hear of FBG sensors employed in the monitoring of structures such as aircraft, bridge, roadways, buildings, ships, and spacecraft.

The read-out systems to interrogate a FBG are based on different type of optoelectronic instrumentations, both for static and dynamic measurements. At the present time several commercial and research instrumentations for FBG monitoring are based on expensive, delicate and complicated discrete interferometric setup or tunable filter made by electrooptic crystals, like lithium niobate.

In this work we experimentally demonstrate that a Fabry-Perot cavity, integrated in a low-loss all-silicon rib waveguide, and realized by standard microelectronic technological processes, can be advantageously employed as a tracking element in a FBG monitoring system, with performances comparable to those of reference instrumentations. The possibility to use a silicon based cavity allows to reduce the production cost, reduce the weight and increase of the robustness of the read-out system.

The system of interrogations is based on an interferometric scanning method; i.e. the variations of the Bragg wavelength are evaluated by mean of the Fabry-Perot cavity tuning. In particular, the reflected signal from the FBG sensor passes through the Fabry-Perot cavity which is tuned by means of thermo-optic effect (i.e. the refractive index variation due to a temperature variation). The optical circuit ends with a photodetector that, for each tuning step, produces a photocurrent proportional to the product convolution integral between the FBG and the tuned FP spectral response. If the FBG sensor undergoes a variation, the wavelength of the reflected radiation is subjected to a shift. Consequently, the new signal detected by the photodiode achieves a phase shift respect the previous one. Retrieving this phase shift by means of an interferometric analysis based on a Fast Fourier Transform algorithm, the wavelength shift can be calculated.

A comparison between the proposed method and a commercial high-performance Optical Spectrun Analizer shows an experimental accuracy in the order of few tenths of picometers.

6172-34, Session 7

CMOS chip chemical detection system comprising mass-sensitive nanocantilevers

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In this paper, an attempt has been made to design a CMOS single-chip chemical detection system integrating an array of nanocantilevers, ultra-low power signal processing circuits for detection of traces (few molecules) of hydrocarbon-based gases in the environment. Carbon nanotube-based cantilevers have been used for high-sensitivity chemical sensing for on-chip integration with the interface electronics. Cantilevered sensors based on frequency variation have been known for a long time. MEMS (Micro-Electro-Mechanical System) technology has added a new dimension to cantilever sensor technology, which has now advanced to commercially available microcantilever sensors for chemical, physical and biological detection with increased sensitivity due to reduced mass in the range of few nanograms. A wide variety of highly sensitive physical, biological and chemical sensors have been fabricated which are based upon the deflection and resonant frequency variation of microcantilevers when exposed to vapor [1, 2]. These microcantilever type sensors have been fabricated in commercial MUMS (Multiusers MEMS) processes using the polysilicon. The resonant frequency of cantilevers is in few kHz to a few hundred kHz range. The sensitivity is inversely proportional to cantilever thickness. Though the detection sensitivity of microcantilevers in part-per-billion (ppb) to part-per-trillion (ppt) can be achieved due to adsorption-induced forces and resonant frequency due to mass loading can be achieved, however, detection sensitivity in present microcantiolever based sensors is limited due to thickness of polysilicon in present MEMS process. The present limitation in detection sensitivity in microcantilever based sensors can be increased by replacing with nanocantilevers using carbonnanotubes to a level where only a handful of gas molecules can be detected. This is possible by replacing microcantilevers with selectively coated (gas adsorbing material) carbon nanotubes as nanocantilevers.

Each array in a CMOS chip chemical detection system design integrates a carbon nanotube cantilever, diffused heating resistors for thermomechanical actuation, a piezoresistive Wheatstone bridge for output signal from temperature gradient in the Wheatstone bridge near the resonance frequency. This signal is amplified by an instrumentation amplifier. After some high pass filtering the signal is converted into a square wave output through a comparator. The resultant frequency shift is mass-sensitive. The technology used is 0.5 μm n-well CMOS for integration of carbon nanotube cantilever on to the signal-processing chip. Full design and some of the experimental results will be presented in the conference.

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6172-35, Session 8

Future trends in electronic packaging

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No abstract available

6172-36, Session 8

A new device for characterization of mechanical stress caused packaging processes

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This paper reports on a new method for estimation and minimization of mechanical stress on MEMS sensor and actuator structures due to packaging processes based on flip chip technology. For studying mechanical stress a test chip with silicon membranes was fabricated. A network of piezo-resistive solid state resistors created by diffusion was used to measure the surface tension pattern between adjacent membranes. Finite element method simulation was used to calculate the stress profile and to determine the optimum positions for placing the resistive network.

An increased spreading of MEMS technology constantly requires new and customized packaging techniques while cost pressure remains high and is hardly being met by tailored processes. To still satisfy the demanding criteria of quality and reliability negative effects caused by packaging have to be analyzed and characterized as early as possible. Those are reduced subsequently but not entirely removed by calibration.

The combination of both finite element method (FEM) simulation and practical measurements allows the definition of guidelines for positioning sensor structures during the design phase and to significantly reduce residual stress after packaging.

The maximum stress area would be the optimum location to place resistors for measuring the stress profile caused by process temperature changes. Using a time-controlled wet-chemical anisotropic tray etching process membranes were created with individual thickness. This allowed the analysis of various stress scenarios. It has been challenging to produce all membranes within one process step. The silicon test chip was contacted using flip chip technology.

First measurement results show a good agreement with the simulations. In addition it was possible to define design guidelines for the packaging process and to verify existing concepts. Linking FEM simulation with the measurements of piezoresistive resistors allowed validation of the used methods as well as of applied load rations and constraints.

6172-37, Session 9

Manipulation by electrostatic-force assisted probes

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Manipulation of fine objects is one of the important techniques for electronic industries, MEMS, etc. Needle-like probe is the simplest tool of manipulation. When two substances are in contact, adhesions between the substances always arise due to van der Waals force, liquid bridge force, electrostatic force, etc. As the needle-like probe uses the adhesions, it can pick up fine objects without any holding devices. Disadvantage of the probe is that heavy and large objects can not be picked up, because the gravity rivals the adhesions. Referring to electrostatic chucks (ESCs), we fabricated a monopole probe and a dipole probe. The former corresponds to monopolar ESCs and the latter corresponds to dipolar ESCs. By the assistant of external electric power, both can pick up heavier and larger objects than ordinal needle-like probe does. The monopole probe is a tungsten needle of 100-660 micrometers in diameter covered with thin oxide film. The monopole probe can manipulate 40-80 micrometers gold particles on a gold substrate as follows. The probe is lowered until the probe touches the particle. After 40-60V is applied between the probe and the substrate, the probe is pulled up. Then the particle is picked up with the probe. Once the particle is in the air, it stays at the tip of the probe even if the voltage is reduced to 0. For release of the particle, the probe is lowered until the particle touches the substrate and is pulled up without applying voltage. The dipole probe is made of an insulating epoxy resin, and two electrodes are embedded in it. The diameter of the probe is 3.1mm. Different from the monopole probe, the dipole probe attract both conductive and dielectric objects over a gap. The probe jumps up a styrene particle of 3mm over the gap of 1mm by applying 2kV, and it jumps up a gold particle of 0.4mm over the gap of 0.5mm by applying 5kV. For the release, the applying voltage is reduced to 0. As the force of gravity is greater than the adhesions, the objects adhered falls. The assistant electrostatic force of the monopole probe is Johnsen-Rahbeck force same with the clamping force of monopolar ESCs, and that of the dipole probe is gradient force same with the clamping force of bipolar ESCs. Current does not pass through fine objects during the manipulation by the dipole probe. On the other hand, very small current passes through fine objects in the monopole probe manipulation. Fine metal objects can be welded by the monopole probe by applying high voltages as reported in the previous meeting. The dipole probe is used only for manipulation. Considering above features, the monopole probe will be applicable to fabricate tough microstructures for MEMS and micro-machine, involving repair. The dipole probe is applicable to assemble mechanical and electronic parts less than 1mm. If miniaturized dipole probe is fabricated, for example, by the lithographic method, it can be applied to the biological field such as cell manipulation.

6172-38, Session 9

A novel lightweight piezo-composite actuator micropump

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In this paper, we focus on the performance improvement of piezoelectric diaphragms of micropumps. The novel high displacement, high output force, circular LIPCA (Lightweight Piezoelectric Composite Actuator) has been developed for piezoelectrically actuated micropumps. The actuator has been designed and fabricated with oxide based piezoelectric material in combination with carbon fabric and glass epoxy. The characteristics of the actuator were analyzed by using both numerical methods and experiments. A valveless micropump was designed, modeled and fabricated based on polydimethylsiloxane (PDMS) material and the developed circular LIPCA with molding techniques. The circular LIPCA bonded with

a thin layer of PDMS was used as an actuator diaphragm, which is able to provide the comparably high displacement, more than two times that of the conventional piezoelectric one. The displacement of the diaphragm, the flow rate and head pressure of the micropump were then evaluated and discussed. The test results indicate that the designed actuator is a very promising candidate for micropump application and can be used to replace the conventional piezoelectric actuator of micropumps.

6172-39, Session 9

Magnetically actuated micropumps using an Fe-PDMS composite membrane

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Peristaltic and diffuser micropumps have been designed, fabricated and tested to demonstrate the applicability of a novel ferromagnetic polydimethylsiloxane (PDMS) composite material. The pumps consist of two primary parts: a PDMS pump chamber and an Fe-PDMS composite actuation membrane. The composite is made by suspending 1um iron particles (50-70wt%) in PDMS prepolymer, which is cast to form membranes with thicknesses of 200-600um. PDMS pump chambers are cast on SU-8 photoresist molds made by photolithography. The devices' multiple layers, which includes a spacer layer, can be assembled using permanent PDMS bonding techniques or via a reconfigurable clamping mechanism.

Two types of micropumps were created: circular peristaltic and valveless rectification. The latter have either a diffuser/nozzle design or a Tesla conduit. The pumps are operated by moving an external permanent magnet over the device to cause a deflection in the Fe-PDMS composite membrane. Small (<1cm3) NdFeB magnets are mounted on micro-motor shafts to provide continuous operation and electronic control over pump speed. The magnet paths are circular, parallel to the actuator membrane plane for the peristaltic pump but perpendicular to the actuator membrane plane for the valveless rectification pumps. Overall device dimensions are 2cm Å~ 2cm Å~ 1cm (excluding motors) while the pump chambers are between 1-10uL in volume. Stroke volumes of 0-4uL were achieved during operation. Stroke volume and maximum flow rate are dependent on several operational parameters including magnet location, magnet field strength, and motor speed.

Fe-PDMS has material properties which are similar to conventional PDMS. Its density, spring constant, and Young's modulus increase in proportion to the concentration of Fe particles. Magnetic alignment of the iron particles during curing further increases mechanical stiffness. Since PDMS is a preferred polymer for many biomedical applications, the surface properties of the Fe-PDMS composite have been examined. Exposing the composite to aqueous solutions resulted in the corrosion of some iron particles at the surface. This was prevented in later experiments by laminating the composite between thin layers of conventional PDMS. The Fe-PDMS composite has exhibited similar interfacial properties to regular PDMS in that the composite can be bonded to itself, PDMS, silicon and glass.

Using an Fe-PDMS composite presents several advantages over magnetic microactuator designs that utilize permanent magnets embedded in a PDMS membrane. Device design is simplified for three reasons: 1) membrane thickness is not limited by the dimensions of a magnet, 2) magnets do not have to be positioned within the prepolymer, and 3) Fe-PDMS has homogenous and isotropic material properties. For applications where the actuation force should be precisely located, as is the case with embedded permanent magnets, we have demonstrated control over the position, concentration and orientation of the iron particles. This also allows the optical transparency of PDMS to be preserved in regions of a normally opaque Fe-PDMS actuator membrane. The uniform composition of Fe-PDMS and its similarity to ordinary PDMS together support future use of the composite in microfluidics and BioMEMS.

6172-40, Session 9

Nano-interconnection for microelectronics and polymers

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We present characteristics of surface induced polymerzing materials for nano-interconnection between micro-electronic circuit and organic polymers. The proposed nano-interconncetion material has to protect the metal lines and make connection to the additional polymers mechanically and electrically.

We report a surface induced 3-D polymerization of Benzo-Triazole (BTA) on the Cu electrode material that was verified with the Ultraviolet Photoemission Spectroscopy (UPS), X-ray Photoemission Spectroscopy (XPS), and Scanning Tunneling Microscope (STM). The electric utilization of shield and chain polymerization of BTA on Cu surface are contemplated in this study.

6172-41, Session 9

Self-tuning mechanical resonator

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Mechanical suspensions are widely used for a variety of applications in sensing and actuation. In typical sensing applications, these suspensions are operated in their resonant mode, and a shift of frequency is measured to ascertain the measurand. Some sensors incorporate an electronic scheme to tune the resonant mode to increase the bandwidth of the sensor.

Similarly in applications where the suspension is used as an actuator like energy scavenging from ambient vibration, an ability to tune the resonant frequency to the external vibration (with the highest energy) increases the energy conversion efficiency. In some current devices, this active tuning is performed electrostatically or electromagnetically thus using a separate sensor to measure the vibration and needing an external power input.

We present here a novel design concept and analysis of a lateral suspension which is able to tune itself to the vibration signal with the maximum energy. The extra energy pumped into the system by the increasing amplitude of vibration (where the fractional increment in amplitude is assumed consistent through-out the vibration spectrum) is stored by the resonator in a spiral spring. The spiral spring constraints the suspension leading to an increase in its first resonant mode.

The self-tuning suspension is considered of significant utility in vibration energy harvesting and inertial sensing. A single crystal lateral suspension resonating at 11 Hz is fabricated using reactive ion etching, the suspension is demonstrated to increase its resonant frequency from 11 - 100 Hz by the application of an external vibration energy dependent force. Multiple schemes to integrate the tuning characteristics of the current device and energy storage property of spiral springs are analyzed. Further the energy storage density of spirals are analyzed and a proof-of-concept is demonstrated to show the feasibility of self-tuning mechanical resonators.

6172-42, Session 10

Fabrication methods of micrometallic closed cellular materials

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Many current researches have been studied to develop the intelligent materials, smart materials and smart structures. Particularly, passive and active damping functions are becoming increasingly important in terms of vibration control of the structures and energy absorbing system has been required to protect persons from injury during impact of accident. Therefore, these materials which have high-energy absorbability and damping functions are required. Recently, Cellular materials are thought to be used for smart materials because of its unique structure and properties. In this study, a new fabrication method to fabricate a micro or nano-metallic closed cellular material containing different materials from that of cell walls using a spark plasma sintering (SPS) method have been developed. And then the mechanical properties of this material are measured.

The metallic closed cellular material fabricating process by SPS method is as follows: 1) Powdered polymer particles with nano- or micro-meter diameter are coated with a metal layer using electro-less plating. 2) The powder particles are filled in the graphite die and pressed by a pair of graphite punches. 3) Pulsed electric current flows through the particles, an efficient heating located at the contacted are between the particles is offered. After SPS, the closed cellular material is produced.

The microstructure of the powder particles, the green compacts before sintering, the cross-sections after sintering and fracture surface were observed using a scanning electron microscope (SEM). To measure the mechanical properties, compressive tests were performed at room temperature. In addition, damping tests were carried out to estimate the internal friction of this material.

Observation of the cross sections of the specimens shows that cell walls of a nickel-phosphorus alloy are observed as bright parts and the material inside the cell walls is observed as darker parts. This result indicates that these metallic closed cellular materials containing the different material from that of cell walls can be produced using this technique.

The results of compressive tests show that the stress-strain curves have a linear elastic region, a long plateau region and a wavy region. It seems that the presence of the plateau in the compressive stress-strain curve is responsible for the high-energy absorption. Therefore, this metallic closed cellular material seems to have high-energy absorbing capacity. These results show that this material can be utilized as an energy absorbing material.

Young's modulus of this material was calculated using the data in linear elastic region for each specimen. The results show that as the thickness of cell walls

increases, the Young's modulus of the specimen increases. Therefore, it should be thought that Young's modulus of the specimens depended on the thickness of the cell walls of the specimen. Because the thickness of the cell walls of this material can be controlled by metal coating process, it seems that the Young's modulus of this material can be controlled by changing the fabrication processes. These results show this closed cellular materials fabricated by SPS method can be used for smart materials and structures.

6172-43, Session 10

Packaging of an iron-gallium nanowire acoustic sensor

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The development of packaging for an underwater acoustic sensor is more difficult than for a typical microelectronic device because of the need to simultaneously protect the device from the external environment while allowing interaction with it. The bio-inspired acoustic sensor is modeled after the hearing mechanisms in fish and other aquatic animals. Such animals hear by allowing sound to pass through their bodies. The sound waves are transferred from the water through the tissues of the fish to hair cells or cilia which are stimulated by interacting with the sound waves. The goal is to create an underwater acoustic sensor and package that will allow sound to pass through while only interacting with the sensing element. The package will ensure reliability in the underwater environment while not interfering with the sound transmission.

The sensor design incorporates iron-gallium (Galfenol) nanowires grown at the University of Minnesota. The scale of the nanowire arrays requires the employment of MEMS technology for fabrication and packaging. The wires will be grown and bonded onto a GMR sensor. Incoming sound waves will excite the cilia-like wires, thus creating magnetic fields which will be picked up by the GMR sensor. The package for the sensor faces several challenges. It must allow sound to pass though it without affecting the signal quality. Any encapsulating material along with the fluid filling the cavity containing the nanowires must match the acoustic impedance of seawater. Furthermore, it must withstand the pressures faced at the operating depth of typical sonar transducers. The package must also protect the sensing elements and interconnects from the ingress of corrosive seawater.

A package was designed and is being fabricated. The structure of the package includes a cavity etched in to a silicon substrate. A glass lid is anodically bonded to the top creating a channel for sound to travel through. A window is molded into the inlet and outlet and a filler fluid is injected into the cavity. Material selection has focused on the acoustic properties of the window material and filler fluid. A scanning acoustic microscope was employed to determine the speed of sound in possible selections. Certain rubbers and oils have been investigated to find which make an impedance match to seawater and are discussed. The window material must also resist the permeation of salt ions, and sufficient wetting of nanowires by the filler fluid is another critical area to be discussed. Contacts to the sensor are made through metallic traces deposited onto the substrate. The package is designed to seal the nanowires array inside and protect it while minimizing loss due to impedance mismatches at material interfaces.

6172-44, Session 10

Reliability of ultra-thin insulation coatings for long-term electrophysiological recordings

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Advances in neural recording are needed for research into Alzheimer's, Parkinson's, epilepsy, strokes, and spinal cord injuries. At the heart of today's neural recording instruments are microelectrodes which are capable of measuring tiny electrical signals in a biological environment. Such electrodes must be small, stable, biocompatible, and robust. However, it is also important that they be easily implanted into a live subject without causing substantial damage to the surrounding tissue. Any tissue damage can lead to immune responses that interfere with the electrical measurement, preventing long-duration studies. Recent advances in microfabrication and nanotechnology afford the opportunity to dramatically reduce the physical dimensions of the recording electrode, thereby minimizing insertion damage. However, one potential cause for concern is the reliability of the insulating coatings, which are typically applied to the electrodes to precisely control the measurement area. For example, conventional metal microelectrodes for extracellular recording are often comprised of tungsten with a sharpened tip (150-250 microns in diameter, 1-2 microns tip). A polymer coating (1-3 microns thick) is applied to all but the tip, resulting in nominal electrical impedances between 0.5-2 Megaohms. During use, however, the polymer can degrade, changing the exposed surface area and, as a result, the impedance of the electrode. As the dimensions of the electrode are reduced from several hundred microns to a few hundred nanometers (and potentially later to only a few nanometers), the reliability of the insulating coating becomes even more critical. As the coating thickness is reduced commensurate with the electrode diameter, any defects in the coating become more significant. In this work, solution processing has been used to deposit ultra-thin ceramic coatings (~100 nm thick; aluminum oxide) onto small metal microwires (25 microns in diameter). Processing conditions were varied to determine their effect on measurement reproducibility and stability during two-electrode impedance measurements in Ringers solution. The coatings were applied to six different metals to determine any differences in performance due to the surface characteristics and properties of the underlying metal. In all cases, sintering temperature was found to have a significant effect on coating degradation, with those coatings processed above 600 °C providing relatively stable readings when addressed periodically over a 48-hour period. However, dielectric breakdown could still be observed in these ultra-thin coatings when even low voltages were applied, indicating that the voltages used for neural recordings must be kept to an absolute minimum.

6172-46, Session 10

Utilizing aperiodic excitation of microelectromechanical systems (MEMS) for microstructure fault detection and improved system functionality

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As MEMS find application niches in an increasingly wider range of systems and platforms, nonstandard methods of device excitation are being explored as a means to achieve the desired sensor or actuator functionality. One such nonstandard method, chaotic excitation, has been used as a research tool to understand nonlinear behavior in microsystems. An extension of this work involves the use of chaotic excitation and other nonlinear phenomena to provide detailed device state information, and to enhance device operation. In order to fully understand how a MEMS device will behave under aperiodic chaotic excitation, a Veeco Instruments Wyko NT1100 optical profilometer with dynamic MEMS (DMEMS) measurement capability has been used to observe 3-dimensional motion of a chaotically excited lateral comb resonator (LCR) device. This briefing presents theoretical modeling results based on measured parameter values that are validated by experimentally measured chaotic displacement data. Methods of using this chaotic output data for pre-packaging and in situ MEMS fault detection are discussed. The application of chaotic driving schemes to improve the sensitivity of MEMS-based inertial and chemical sensors is discussed as well.

6172-47, Session 11

A comparative study of MOEM pressure sensors using MZI, DC and racetrack resonator IO structures

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In recent years MEMS (Micro Electro Mechanical System) sensors have drawn considerable attention due to their attraction in terms of miniaturization, batch fabrication and ease of integration with the required electronics circuitry. Pressure sensing is currently the most lucrative market for solid-state micro sensors. Notable applications are blood pressure sensing, industrial process monitoring and automotive engine control. Although MEMS sensors based on piezo-resistive or capacitive measurement is popular they show poor response in electromagnetically active environment. This is where Micro-opto-electro-mechanical (MOEM) based sensors which combine MEMS with Integrated Optics (IO) become important[1]. They are immune to EMI and can offer larger bandwidth and higher sensitivity.

In this paper we compare the performance characteristics of three types of MOEM pressure sensors based on Mach-Zehnder Interferometer (MZI), Directional Coupler (DC) and racetrack resonator (RR) IO geometries[2]. It may be noted that the first two configurations measure the pressure changes through a change in optical intensity while the third one measures the same in terms of frequency or wavelength change.

The analysis consists of mechanical model, optical device model and their interrelationship. The mechanical equations are modeled using an equivalent single layer approximation. The optical wave propagation is analysed using beam propagation method (BPM) in combination with effective index method (EIM). Induced refractive index change is interrelated to impressed pressure through opto-mechanical coupling. In all the three devices the mechanical element considered is a rectangular diaphragm of size 4mm x 1mm x 20 microns and the optical waveguide is an anti-resonant reflecting optical waveguide (ARROW) supporting TM mode that is more sensitive by virtue of its better opto-mechanical coupling. Typically we obtain a normalized pressure sensitivity of 0.101μW/mW/kPa, 0.303μW/mW/kPa and 1.32 pm/KPa in case of MZI, DC and RR devices respectively. We have

analysed the noise performance characteristics for the above sensors. We also present preliminary experimental results for the above pressure sensors.

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6172-48, Session 11

Transfer-function characterization of a thermally-actuated, electrostatically-sensed displacement-amplification MEMS

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A transfer-function (TF) approach is proposed in this paper which characterizes the behavior of a thermally-actuated, integrated electrostatically-sensed microelectromechanical system (MEMS) in order to perform a system identification enabling further controlled operation of the microdevice. By considering the input to the system is the current/voltage and the output is the amplified mechanical displacement, a chain TF is derived which includes energy losses due to the imperfect energy conversion from electric to thermal, and which correspond to various phenomena, such as convection, radiation and conduction - accounting for a Joule-effect temperature less than the ideal (theoretical) one. This TF also includes the relationship between temperature and the mechanical deformation of both the active flexure hinges, which are thermally-actuated, and of the passive ones, which realize the output motion of the microdevice. This TF model is validated by means of experimental data from an actual displacement-amplification MEMS which was fabricated by means of the PolyMUMPS surface machining technology, and also through finite element simulation. Based on the TF, several simulations have been performed comprising determination of the microsystem's resonant frequency and evaluation of the output in terms of various inputs, such as unit step or unit impulse.

6172-49, Session 11

Experimental validation and testing of an active damping control strategy for micromachined mechanical vibration isolation filters using electrostatic actuation

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Missiles, rockets and certain types of industrial machinery are exposed extreme vibration environments, with high frequency/amplitude mechanical vibrations which may be detrimental to components that are sensitive to these high frequency mechanical vibrations. This is particularly true for micro-devices, such as MEMS gyroscopes and resonators, oscillators and some micro optics. Exposure to high frequency mechanical vibrations can lead to a variety of problems, from reduced sensitivity and an increased noise floor component failure to the outright mechanical failure of the device. One approach to mitigate such effects is to isolators tuned to the frequency range of concern. In this regard, passive micromachined silicon lowpass filter structures (spring-mass-damper) have been developed and demonstrated. However, low damping (especially if operated in near-vacuum environments) and a lack of tunability after fabrication has limited the effectiveness and general applicability of such systems. Similarly, a variety of active filter topologies, such as piezoelectric, electrostrictive-polymer-film and SMA have also been investigated in recent years.

At present, electrostatic actuators have been utilized to produce mechanical movements in a variety of micromachined devices. Such devices offer the advantages of low power, fast response time, compatibility with silicon micromachining, capacitive position measurement, and relative simplicity of fabrication. This paper presents the development and experimental validation of an approach for realizing active micromachined mechanical lowpass vibration isolation filters by integrating an electrostatic actuator with the micromachined passive filter structure to realize an active mechanical lowpass filter. The electrostatic actuator is used both as the control loop actuator and the proof mass position sensor. Electronic signal processing is used to generate the appropriate actuator control voltage to obtain the desired filter characteristics. Although the electrostatic actuator can be used to adjust the filter resonant frequency, the primary application is for increasing the damping to an acceptable level. The physical size of these active filters is suitable for use in or as packaging for sensitive electronic and MEMS devices, such as MEMS vibratory gyroscope chips. The resulting electromechanical system-in-a-package allows for optimum system performance through allowing the use of state of the art components in mechanically harsh environments.

6172-50, Session 11

Wireless power technology for application-specific scenarios of high-altitude airships

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The power technology for high altitude airship (HAA) that offers a long-duration maneuver and applications must come from nature, e.g. solar power, since the airships lighter than air do not have much room via their weight budget for conventional liquid fueled power generation systems. A conceptual study for the HAA power budget plan has been done at NASA Langley Research Center by utilizing new nanotechnology materials for power harvesting and power transmission by microwave. The power harvesting in this study considered using advanced thermoelectric (TE) materials that have a targeted figure of merit (FOM) goal greater than 5. A FOM of 1 is equivalent to an efficiency greater than 6%. The major reason to utilize the advanced TE materials is the cascaded efficiency of multi-layer TE modules that are much higher than the efficiency of a single layer. The layered structure of the advanced TE materials is specifically engineered to provide maximum efficiency for the corresponding range of operational temperatures. For three layers of the advanced TE materials that operate at high, medium, and low temperatures, correspondingly in a tandem mode, the cascaded efficiency is greater than 60 %. It is like a regenerative cycle system. Accordingly, the advanced TE materials which are under development at NASA Langley Research Center are the basis of HAA power budget plan. The overlong cross-sectioned HAA with a 500 ft long, 200 ft wide, and 80 ft high configuration receives the total incident solar power of 9 MW. Using 20% efficient PV cells, the converted power would be less than 2 MW. With advanced TE materials of the same efficiency, the converted power would be greater than 4 MW because of the cascaded efficiency of three layers is approximately 49%. Considering a three-layered structure of the advanced TE materials with the FOM 5, the cascade efficiency approaches 66 %. By the amount of losses due to geometrical orientation, reflection, and transmittance, the obtainable power amounts to 3.84 MW. For nighttime operation, microwave power transmission is utilized to feed the power required for HAA operation. The harvested power can be utilized for power transmission to UAVs, for directed energy weapons such as a high energy laser, and for internal power requirements such as propulsion and control. These applications require a continuous power source that will run for several hours in a sequential or pulse mode. The detailed study will discuss both the HAA power budget plan based on the tandem mode of advanced TE materials layers and the new class of light weight UAVs that will be powered via microwave energy.

6172-51, Session 11

Ultrawideband RF/microwave MEMS switches operating at MM-wave frequencies

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MEMS switches offer ultra high reliability and most compact structure unmatched by any other switch configuration. Measure of a switch performance can be described by the Figure-of-merit (FOM) or by the cutoff frequency. The computed cutoff frequency for an electronic switch using GaAs-FET devices is 280 GHz, 420 GHz using GaAs-pHEMT devices, 730 GHz using GaAs-PIN diodes, and 11,369 GHz using MEMS technique. A MEMS switch comes in two configurations, namely, series and shunt.

A MEMS switch with a series configuration is most popular and it consists of a flexible S-shaped film with a switching contact, rolling between a top and a bottom electrode in electrostatic "touch-mode" actuation. This switch configuration requires large separation between the beam and the substrate and relatively high actuation voltage to achieve high RF isolation in the OFF state. A large contact area is highly desirable for switching signals with high current levels. Since, the RF part and the MEMS part are processed on separate wafers, high yield is possible, leading to a cost-effective and reliable design.

RF simulation data indicate that improvement in OFF state isolation is possible at gap distances ranging from 10 to 16 microns. The S-shaped film actuator design offers high isolation irrespective of low actuation voltage, even at very large overlapping switch contact area. A MEMS switch with series configuration demonstrated an insertion loss of less than 0.1 dB from DC to 20 GHz. This switch demonstrated isolation better than -45 dB at 2 GHz, -30 dB at 15 GHz, and 27dB at 20 GHz, while operating at 15 V.

It is important to mention that a metal-to-metal shunt RF-MEMS switch fabricated on a semiconductor GaAs substrate is compatible with standard microelectronic processing technique. This switch separation posts eliminate the sticking failure, thereby yielding high reliability. This unique design feature of the shunt switch provides very high reliability even at actuation voltage as low as 15 V, which is not

possible with RF-MEMS switch with a series configuration. The switch demonstrated an insertion loss less than 0.25 dB and isolation better than -22 db at 40 GHz-operation.

The pull-in voltage also known as actuation voltage of a mechanical structure is dependent on the spring constant (K), the gap (g) between the switch and the actuation pad, and actuation area A. An actuation voltage much less than 20 V can be achieved with gap not exceeding 2 microns with spring constant less than 2 N/m. A lower spring constant is necessary for low voltage operation, which is only possible with increased cantilever length. In summary, optimization of the cantilever and its geometry is absolutely necessary to achieve actuation voltage between 10 to 15 V. Implementation of the above design requirements will yield insertion loss less than 0.1 dB and isolation better than -22 dB for RF frequencies up to 40 GHz, which can be extended to 75 GHz by optimizing switch design parameters using software. Sticking of moving parts in the MEMS switch presents a major reliability problem. Potential applications include electronically steerable antennas, wireless communications, drone electronics, missile seekers, and UAV imaging sensors.

6172-52, Session 11

Design and development of microstrip patch antenna at Ka-band using MEMS technology

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Microstrip antenna is a very common element in telecommunication and radar applications. The advantages of microstrip antenna include low-profile, low-cost, light-weight and ease of integration with microwave integrated circuits which results in high-performance antenna arrays. Implementing the System-on-Chip (SOC) concept requires that all the passive and the active components must be integrated on the same substrate. Silicon is the most commonly used substrate for RF MEMS. However, its high relative dielectric constant (εr = 11.9) limits the performance of the antenna fabricated on the silicon substrate. This is attributed to the easy excitation of surface waves resulting in lower bandwidth, limited power handling capability and degraded radiation efficiency of an antenna. Another issue is the losses caused by the silicon conductivity. This problem is somewhat overcome by using high-resistivity silicon (HRS) substrates. In this paper, we propose a microstrip patch antenna designed and fabricated on a thin sputtered silicon dioxide membrane on a silicon substrate using MEMS technology. The SiO2 membrane formation is one of the last steps in the process sequence employed to realize the system-on-chip. For this reason, it would be advantageous to use a low temperature technique to form SiO2 so as not to adversely affect the already fabricated components on the same silicon substrate. RF sputtering appears to be an attractive option for depositing SiO2 films for membrane formation and this is the motivation for the present work. It has added advantage over the other low-temperature deposition techniques (plasma CVD, photo CVD etc.) as no toxic / hazardous gases are involved in the deposition process and the same sputtering system can also be used for metal layer(s) required for antenna fabrication. The SiO2 film is deposited on a high resistivity (100) silicon substrate in a standard RF (13.56 MHz) sputtering system (Alcatel) using a 3-inch silicon dioxide target and argon ambient. The process was carried out in “sputter-up” configuration. The sputtering pressure and RF power were in the range 5 -10 m Torr and 150 - 250 W respectively. After silicon dioxide deposition, Cr-Au is sputtered in the same system and patterned to form the patch antenna. A cavity is then formed below the patch area of the antenna by completely etching silicon from the back side of the wafer using anisotropic etchant. While the patch is realized on the suspended silicon dioxide dielectric membrane, the feeding network is formed on the bulk silicon substrate.

This process synthesizes a low dielectric constant region (air cavity, $\varepsilon r \approx 1$) around the antenna and thus results in enhanced bandwidth. The proposed configuration provides great ease in fabrication as no etch-stop layer is required. Complete 3-D full-wave analysis is done using Agilent’s High Frequency Structure Simulator (HFSS). The simulated return loss is -24 dB at 35 GHz and the bandwidth is 3.6%. The directivity and E-plane / H-plane beamwidth of the antenna at 35 GHz are 9.4 dB and 60 degrees respectively. The structure is also analyzed to study the effect of membrane thickness and dielectric constant variations.

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6173-01, Session 1

The fabrication and deformation capabilities of two and three dimensionally graded DEPP FGP

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Functionally Graded Piezoceramics (FGP) is an emerging technology whose full potential has yet to be harnessed. These materials employ spatially gradients of specific material properties within a continuous piezoceramic to produce internal strain gradients that result in deformations of higher-order than the axial displacements exhibited by homogeneous piezoceramics. Material gradients across one dimension (usually the beam/plate thickness) produce bending deformations similar to conventionally constructed, layered actuators such as bimorphs. The untapped capabilities of FGP lie in their ability to produce even more complex deformations through varying the material properties across multiple dimensions.

Many researchers have successfully created one dimensional FGP by varying material resistivity, conductivity, stiffness, piezoelectric coefficients, permittivity, or even the porosity of the material. The manufacturing processes used to fabricate these FGP are as diverse as the gradient techniques, and include powder pressing, tape casting, centrifugal casting, selective reduction, and electrophoretic deposition. However, due to the limitations inherent to these processes, it is extremely difficult, if not impossible, to produce two and three dimensional property gradients. Multidimensional FGP can be achieved through coupling the Dual Electro/Piezo Property (DEPP) gradient technique with an expanded Micro-Fabrication via Co-eXtrusion (MFCX) process. The synergistic variation of both the piezoelectric coefficients and electric permittivity of the DEPP technique and the thermoplastic nature of the MFCX media allow for easily produced, precisely controlled material gradients across two and three dimensions that produce FGP specimens capable of warped, rippled, and even dimpled deformed states.

This paper presents multi-dimensionally graded piezoceramics employing the DEPP gradient technique which combines American Piezoceramic's lead zirconate titanate (PZT) based 856 composition doped with Ferro's high permittivity barium titanate (BT) based dielectric powder, Z9500. The PZT/BT gradient concentrates the applied electric field in the material with a larger piezoelectric effect, simultaneously increasing the deflection and electric efficiency of the FGP specimen. Since the technique also preserves the resistive properties of the material, complex material gradients across all spatial dimensions can be created without the electrical shorting problems conductive constituent materials would experience. The co-extrusion process was used to produce thermoplastic building blocks (i.e. beams and patches) with a material gradient across their thickness. The blocks can be arranged within a die to form two and three dimensional gradients and subsequent hot pressing yields an FGP preform where the building blocks have fused into a monolithic sample. After a polymer burnout and sintering process the result is a continuously graded, fully dense two or three dimensionally graded piezoceramic.

This process was used to create a two dimensionally graded beam that ripples upon activation. The FGP prototype was constructed from three beam building blocks arranged end to end with the middle section possessing a thickness gradient opposite to the adjacent pieces. This 2D gradient scheme produces a deformed shape consisting of two peaks with a valley in between. The three dimensionally graded plate was an extension of this prototype in the third dimension, using nine square patch building blocks to create a dimpled surface where adjacent squares have opposite curvatures when electrically activated producing alternating convex and concave dimples. These two prototypes merely scratch the surface of the capabilities of multi-dimensional FGP where custom gradients could be fabricated to produce distributed actuators which warp and dimple to varying degrees to provide tailored actuation across large surfaces.

6173-03, Session 1

Behavior of unimorph rectangular piezoelectric diaphragm actuators

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This paper presents a study in which clamped unimorph rectangular piezoelectric diaphragms are analyzed to determine the importance of the pattern of the electrodes that supply the driving charge to the actuator. There has been a great deal of interest in getting better performance out of piezoelectric actuator technology, which in simple terms means getting increased actuator deflection out of smaller devices with lower input power. In previous work, it has been shown that the clamped circular diaphragm can generate much increased deflection in response to an electric loading when the electrode has a "regrouped" pattern. Regrouping refers to the process of segmenting the electrodes into regions that are electrically disconnected and then reconnecting those regions such that some have reversed polarity. The rectangular diaphragm actuator was studied in this paper to determine the effects of electrode patterns, boundary conditions, and shape of the piezoelectric layer on the actuator's static displacement.

6173-04, Session 1

Active-passive hybrid piezoelectric actuators for high-precision hard disk drive servo systems

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Positioning precision is crucial to today's increasingly high-speed, high-capacity, high data density, and miniaturized hard disk drives (HDDs). The demand for higher bandwidth servo systems that can quickly and precisely position the read/write head on a high track density becomes more pressing. Recently, the idea of applying dual-stage actuators to track servo systems has been studied. The push-pull piezoelectric actuated devices have been developed as micro actuators for fine and fast positioning, while the voice coil motor functions as a large but coarse seeking. However, existing dual-stage actuators have very poor shock performance, because the current design uses piezoelectric patches only. In this paper, we propose a novel dual-stage servo system using enhanced active-passive hybrid piezoelectric actuators. The proposed actuators will outperform the existing dual-stage actuators for much higher shock resistance and reliability, due to the incorporation of passive damping in the design. We aim to develop this hybrid servo system to improve the reliability and precision of track-following servos in HDDs. New piezoelectrically actuated suspensions with passive damping have been designed and fabricated. In order to evaluate positioning and track-following performances for the dual-stage track servo systems, experimental efforts are carried out to implement the synthesized active-passive suspension structure with enhanced piezoelectric actuators using composite nonlinear feedback controller. The shock resistance capability of this hybrid servo system will be also studied during the track-following operation.

6173-05, Session 1

Design of a two degree of freedom shape memory alloy actuator for mirror positioning

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Due to improvements in material properties through research, actuation mechanisms utilizing shape memory alloy (SMA) have attracted more attention. Many actuation mechanisms have utilized the phase transformation of SMA's to generate motion. One new arena for the application of the alloys is the automotive industry, where they can reduce size and cost of the actuator in current models. The three major types of actuators employing SMA wires will be discussed. Antagonistic actuators are one of the types that have begun to find applications where position can be controlled through the use of SMA wire. Based on this antagonistic actuator, a novel two degree of freedom SMA actuator is proposed that controls the position of an external rear view mirror. This design would replace the currently used DC motor design with a cheaper and more compact mechanism. The prototype concept is implemented using the antagonistic actua-

tor based on SMA wire, a joystick and a microcontroller. Matlab Simulink(r) and dSPACE(r) control packages were used to design a control method for the microcontroller. Data collected from testing of this mirror will illustrate the effectiveness against an existing mirror that is used in a moderately expensive car. Also within this data collection is a study of the effects of outside temperature on the mechanism and general operation.

6173-06, Session 2

Dynamic testing and modeling of NiMnGa ferromagnetic shape memory alloy

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The dynamic behavior and performance of ferromagnetic shape memory alloys (FSMA) like single crystal NiMnGa is the current subject of interest. Qualitatively, FSMA combine the strain generation potential of thermal SMA with the bandwidth of magnetostrictives like terfenol. The strain generating capability and energy density of these materials is large as compared to other active materials. One of the most common types of FSMA, NiMnGa, has been reported to produce strains on the order of 10-20%, although 5-7% is more likely. To produce sufficient strain amplitudes, many active materials, like piezoelectrics, require stroke amplification stages. These mechanisms are often mechanically complex and incur significant weight penalties and frictional losses. Because of these drawbacks, active materials like NiMnGa, capable of producing large strain amplitudes without amplification are especially valuable to the smart structures community. FSMA driven actuators have the potential to provide a more compact, mechanically simpler alternative for actuators implemented in integrated smart systems.

The dynamic behavior of the alloy is characterized by measuring the response of NiMnGa rods subjected to a wide range of axial loading conditions. The effects of varying levels of constant pre-strain and constant preload are studied as well as the effect of bias fields on material behavior. The first set of tests includes evaluating the force response in a dynamic field on the order of 1 Tesla in amplitude at a constant pre-strain. Pre-strains ranging from 0 to 5% are studied. The second set of tests includes the evaluation of the strain response in a 1 Tesla dynamic field at various levels of constant preload. In addition to the stress-strain response of the material, performance characteristics such as electromechanical efficiency, power output and power density are also measured.

Although the material has been reported to have a bandwidth well into the kHz range the scope of these tests will be limited to a much narrower band. So far, because of restrictions in the test equipment, material behavior has been observed for frequencies less than 10 Hz.

Because relatively few analytical tools exist for FSMA, a basic analytical model incorporating the experimental results of the characterization is proposed. The model is used to predict NiMnGa behavior and then compared to the experimental data in order to evaluate its accuracy and validity. A comparison between the new model and existing analytical tools is provided in order to provide context for future FSMA research.

6173-07, Session 2

Fatigue property of a conducting shape memory

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This paper presents the fatigue properties of conducting shape memory polyurethane actuators and its practical application as an actuator. Two years ago, a concept of shape memory polymer actuated by electric power was introduced in this conference [1], while conventional shape memory polymer is activated by external heat. A conducting shape memory poly-urethane (CSMPu) was manufactured by adding carbon nano-tube to shape memory poly-urethane. Last year, we could find a method to enhance the dispersion of carbon nano tube in polyurethane which was main obstacle to be used as an actuator [2]. This year, the fatigue property of CSMPu has been investigated with durability test. The maximum number of actuation cycles of CSMPu was determined under normal actuation condition. And basic mechanical data such as stress-strain relationship, Young's modulus and Poisson's ratio have been measured to design CSMPu actuators. Finally, we try to design practical CSMPu actuator with consideration of mechanism.

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6173-08, Session 2

Preliminary controls development of high-temperature shape memory alloy actuators for intelligent aircraft propulsion systems

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Future advanced aircraft propulsion systems are being developed to incorporate intelligent/smart technologies into their designs, which are expected to enable cleaner, safer, quieter, more economical, and more efficient aircraft engine operation. High temperature shape memory alloys (HTSMA) are being developed to be used in smart actuators and sensors for intelligent aircraft engines. These materials, when deformed from an initially set configuration, possess the ability to remember that previously set structural configuration when heated to a characteristic transformation temperature. They also possess nonlinear thermo-mechanical and electro-mechanical characteristics as well as high-temperature effects that may impede their practical use. In order to use these materials in a robust and reliable manner, the actuator control system must be able to compensate for these characteristics. This paper reports on the preliminary controls development of HTSMA based actuators that address these issues, with a particular focus on modeling and controller selection, along with analysis, simulation and bench-top material performance tests.

6173-09, Session 2

Modeling and pressure control of hydraulic pumps with ferromagnetic shape memory alloys (FSMAs) actuators

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FSMAs like Ni2MnGa have attracted significant attention over the last few years. What makes these materials attractive as actuators is their high energy density, large stroke, and high bandwidth. Furthermore, these properties make FSMAs potential candidates for developing Solid-Fluid Hybrid Actuations (SFHA). The FSMA actuator functions as the transducer of the pump providing the mechanical energy by the linear reversible displacement. In order to develop effective hydraulic pumps with FSMA actuators, it is important to study their dynamic behavior in the chamber full of the working fluid. In this paper a dynamic model is presented for a hydraulic pump with Ni2MnGa transducer. The pump consists of two active valves, a chamber, a diaphragm, and a Ni2MnGa actuator. An enhanced phenomenological model is proposed to describe the strain output of the actuator in the response to magnetic field strengths. Then, a model based control algorithm is developed to regulate the pressure within the chamber. Simulations demonstrate the effectiveness of the algorithm.

6173-10, Session 2

Mechanical extension implant for short-bowel syndrome using shape memory alloy actuation

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Short-bowel syndrome (SBS) is a rare, potentially lethal medical condition where the small intestine is far shorter than required for proper nutrient absorption, with no long-term nutritional or hormone-based solution. Surgically modifying the bowel has limited success. Recent studies show that the application of mechanical stress (tension) to the bowel induces cell growth and can produce permanent lengthening. This paper presents the design and testing of two prototype implantable devices which gently apply tension to a length of bowel. As growth occurs over weeks or months, this promises a tremendous advantage over the alternative of attaching an external device to an immobilized patient with an exposed bowel section. Each device is designed to fit inside a short (~10cm) section of bowel (15mm diameter) surgically isolated from the digestive tract, and to slowly extend, allowing the bowel section to grow to approximately double its initial length. Installing and removing the device requires relatively non-invasive surgery.

The first device is a shape memory alloy actuated linear ratchet capable of small (1.25mm) discrete steps taken only once or twice daily. Based on measured force-strain properties of bowel, this step size was designed to avoid overly-large tension (<20g) before the bowel grows to "catch up" with the device. A 10cm length of 0.2mm diameter Nitinol shape-memory-alloy (SMA) wire was chosen for actuation because of the small size constraints, the moderate force requirement and step size, the low actuation frequency, low actuation voltage and current, and for its biocompatibility. The SMA wire pushes a threaded rod via a ratcheting pair of sprung flaps. The actuator parameters and SMA reset spring were designed by combining an experimentally determined SMA force-displacement with a ratchet mechanism model. A 10cm long, 14.3mm diameter prototype was built and its force and motion generation capabilities tested. Electrically actuated with 0.8A, the device easily took full steps under a 20g load, stepped against loads up to

350g, and withstood loads up to 450g before backdriving the ratchet. The prototype could almost double its length, extending to 18cm, and the mechanism is such that the force does not depend on the extended length. The prototype was also tested inside a section of pig bowel (similar to human bowel) demonstrating the ability to stretch the bowel section by 3.8cm: far beyond the stretch required were the bowel allowed to grow.

The second device is a dual concentric hydraulic piston 16mm in diameter, capable of extending from 11.8cm in length to 21.9cm, also almost doubling its length when activated by compressing an external cylinder. The pistons were tested to hold loads over 400g without backdriving. Preliminary data demonstrate that mechanical force, with an intraluminally implanted device, can significantly (~2-fold) lengthen pig small intestine over a 7 day period (enterogenesis). The two devices exhibit similar performance and are both clearly appropriate for the application, but differ mainly in that while the hydraulic piston device is simpler to manufacture, it requires external connections (a hydraulic pump) where the SMA ratchet could have a control and power pack implanted during the growth period.

6173-11, Session 3

Morphing flight control surface system using a highly deformable mechanism

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A novel Morphing Flight Control Surface (MFCS) system using a Highly Deformable Mechanism (HDM) is presented. The feasibility of this technology for the applications of deformable wing structures, such as airfoil shaping, warping, or twisting with a flexure-based high displacement piezoelectric actuator is demonstrated via computational simulations such as Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD). Then, complex potential flow theory, kinematics, geometry, and static force analysis are incorporated into a multidisciplinary GUI simulation tool. This tool has been used to aid design of the MFCS. The results show that one can achieve wing deformations with the proposed system while adding minimal volume, power, and weight to the wing.

6173-12, Session 3

A simple mechanical system for a flapping wing MAV: modeling and experiments

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The Micro Aerial Vehicle represents a strategic and industrial goal. The challenge is truly technical, as the needs are very specific in terms of mission and efficiency. The aerospace French agency (Onera) has launched an internal program on that purpose including many research topics, essential to understand how to reach the goals. Thus, aerodynamic (generally unsteady with low Reynolds number), structural dynamics, propulsion, actuation, control,.. are being studied in this field. Because the problem is very large, we found interesting, not only to analyze and formulate, but also to look how nature proceeds. As a matter of fact, many solutions are existing among flying animals, and we found not so meaningless to get inspired by biology. Thus, on a mechanical actuation point of view, it has been interesting to note some insects ability, particularly those using their own structure for the actuation. Hence, biologists have discovered that resonance is the key to flight efficiency for some insects (e.g diptera). Indeed, for flapping wings this behavior seems to insure the best compromise between high flapping angle, effectiveness and simplicity of the mechanics. This statement was part of our reflection in designing a mechanical structure for flapping wings. This structure can be seen as made of two springs. The first one, U shaped, is linked to the second, a bended pre-stressed shell closing the U form, by the upper part. The links between this two springs are made through two small hinges, ensuring free oscillations of the shell spring. As wings are fastened to this last spring, the structure can be seen as a thorax of insect. But the upper part is playing the role of a special tergum, as it allows large flapping angle. Such a system can be studied by means of a reduced dynamic system, leading after some simplifications to a non linear formulation of the flapping movement. Indeed, after normalization one can found a formulae equivalent to a classical Duffing differential equation, characterized by a possible chaotic behavior when excited periodically. Such a behavior, easily explained by an amplitude dependency of the resonant frequency, is obviously not compatible with what is seeked. Hence, we made a study to identify the stability domain of this system under actuation. This has been conducted theoretically and experimentally. But because of some limitations in the experiments and the actuation, not all the results could cover the theoretical investigations. However, some main features of the movement were obtained and are discussed in this paper. They show that the resulting flapping movement can induce inertial wings torsion. The study of the 2 d.d.l. reduced dynamic system (flapping & torsion) exhibit a matched behavior to what is needed for some wings to twist when it's time. This is consistent with what has been observed in the real world. Finally, we found, theoretically, the same feature when synchronizing the "actuation" to the oscillating structure. That solution is a promising concept as it insures an always stable behavior.

6173-13, Session 3

An improved flapping wing system actuated by the LIPCA

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Nowadays, the study of flapping flight of the nature's flyer has received much attention due to its superior flight performance compared with any fix or rotary wing that human made. Nature's flyer, particularly insect uses special technique related with wing motion to generates high force during flapping flight. The three-dimensional shape of the wing also has significant contribution in vortex generation that can amplify the obtained force. The biomimetic design of flapping robot that mimic the flapping technique of the insect is hard to develop, since it should be able to create complicated wing motion such that the insect's. During flapping, the insect also rotate its wing to maintain the angle of attack relative to the local wind, so that the insect still can produces positive lift, even during the upstroke motion of the wings.

In this paper we present our improved design and demonstration of a flapping device actuated by LIPCA (Lightweight Piezo-Composite Actuator) for mimicking the insect's flapping. The device uses a four-bar linkages mechanism for converting and amplifying the actuation displacement of the actuator into a large flapping motion of the wings. The special wing-joint for the feathering mechanism is also implemented such that the wing can rotate during flapping. This mechanism is implemented because the lift and thrust should be generated even during the upstroke. Depending on the size and mass of the wing, the device can generate high flapping frequency ranging from 10 to 20 Hz. The wing is designed mimicking a real insect wing that has a zig-zag shape of cross section, which is good for vortex generation during the flapping flight in the low Reynolds number. Various wing patterns and positions relative to the body are used for investigating the mechanism of vortex generation, which is very useful to produce high lift in the flapping flight. By using a specially designed lift measurement system, we can determine which configuration is better in producing the forces. The visualization of the generated vortex during flapping motion is also provided by using a high speed camera. The paper will present more detail of the measured data.

6173-14, Session 3

Design of micro-aerial vehicle (MAV) elevator actuated by LIPCA

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Recently, there has been a persistent interest in high performance actuators suitable for the actuation of control surfaces of small aircraft and helicopter blades and for active vibration control of aerospace and submarine structures that need high specific force and displacement. What is really needed for active actuation is a large-displacement actuator with a compact source, i.e., much higher strain. A lot of effort has been made to develop compact actuators that can produce large displacement and/or high force.

One of the representative actuator is the LIPCA (Lightweight Piezoceramic Composite Actuator) that was introduced by Yoon. The LIPCA design offers the advantages to be applied as actuator in small aerial vehicle compared to any other actuators. The weight is one of the main concerns for aerospace field, and since LIPCA has the lighter weight than any other piezo-composite actuators thus it is suitable as actuator for small aircraft control surface.

In this paper, the conceptual design of LIPCA-actuated elevator is introduced. The simple analytical model and FEM modeling were employed to predict the deflection angle of the elevator. The hinge moment that produced by the arodynamic forces was calculated to determine the optimum position of the hinge point, thus the elevator can produce the deflection as high as possible with reasonable hinge moment. To verify the prediction, a prototype of MAV elevator was manufactured. The wind tunnel test is being conducted and the test results will be compared with the numerical analysis results.

6173-15, Session 3

Post-buckled precompressed (PBP) piezoelectric actuators for morphing wing UAV flight control

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This paper describes the use of a new class of flight control actuators employing Post-Buckled Precompressed (PBP) piezoelectric elements to control the flight of

Uninhabited Aerial Vehicles (UAVs) through section morphing. The PBP principle produces significantly increased deflections per Volt/m of the piezoelectric actuator elements and is implemented using axial precompression. To demonstrate the principle on a flightworthy UAV, morphing wing panels employing NACA 0012 airfoils and PBP actuators on the aft 60% of the camber line were used in place of ailerons on a 1.40 m span conventional configuration subscale UAV. Each of the morphing wing panels was built with an elastic skin to allow for shape deformation and at the same time apply an axial compression on the piezoelectric actuators. Quasi static bench tests showed that due to this axial compression deflection levels were increased with a factor of two up to +/- 7.5° at a corner frequency of 38 Hz. This new wing was built with morphing wing panels on the outer 33% of the semispan. It experienced a 9% weight reduction with respect to the original wing, which did not employ any wing movables. Flight tests showed excellent roll control due to wing morphing. The derivative of the two dimensional lift coefficient, Clδ , with respect to the deflection, δ, showed an average of Clδ=0.142 [1/deg]. A second morphing wing, employing PBP actuators on the aft 70% of the camber line was built to impose roll and direct lift control for a 50 cm span subscale UAV. This wing consisted of an aerodynamically shaped leading edge and a thin flat rear part which could be curved by the PBP actuators to induce control. Precompression of the actuators was ensured by means of rubber bands. Static bench tests showed that due to precompression deflection levels were increased with a factor of two up to +/- 7°. Wind tunnel tests showed that a change in camber of the aft 70% of the airfoil resulted in an average Clδ=0.176 [1/deg]. The paper concludes with flight test results showing roll control increments superior to the baseline conventional UAV as well as a net reduction in flight control system weight, volume, power consumption, and drag for minimal part count. Both morphing wing concepts showed that PBP piezoelectric actuators have significant benefits over conventional actuators and can be successfully applied to induce aircraft control.

6173-16, Session 3

Smart flapping wing using macrofiber composite actuators

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Bird and insect flight has fascinated humans for many centuries, and the imitation of their flapping wing flight has been the oldest aeronautical dream. Numerous efforts have been made to make flapping flight vehicle named ornithopter. It uses the flapping motion of the wings like birds and a positive trim angle produced by adjusting the mass center and stabilizer to increase the lift. However, cruising birds and bats fly with horizontal flapping axis and their flight efficiency is fairly higher than that of the ornithopter. They also use the twisting and folding motions to attain the effective incident angle and reduce drag of the wings. By adaptation of the skeletal and muscular systems, they can generate additional flight motions such as modification and reversal of camber between upward and downward strokes, wing area expansion and contraction, and transverse bending. Due to these complicated motions, the flapping flight has not been completely analyzed. In this paper, aerodynamic characteristics of the flapping wing flight according to camber and shape changes of the wings by using Macro-Fiber Composites (MFC) are investigated.

We manufactured two biomimetic flapping wings with the span of 54 cm and the aspect ratio of 4.3. The wings consist of graphite/epoxy composite frames and flexible thin skin of a PVC film. To control the camber and shape of the wings, two MFC (M8528P1, d33 type) actuators are embedded between the frame and skin at the distance of 8.5 cm from the flapping axis on the left and right wings. The flapping motion of the wings is generated by the use of an electric motor and a transmission system which converts the rotary motion of the driving motor into the flapping motion. A wind tunnel test stand with two force loadcells is fabricated to measure the lift and thrust simultaneously, and the incidence angle of the flapping axis can be changed by adjusting a fixture held on the test stand. The voltage range from -500 to 1500 V is applied to the MFC actuators and the maximum excitation frequency is 12 Hz. The trailing edge of each wing can be deformed up to 13% of the cord length. The flapping angle and displacement are measured by the use of a laser Doppler vibrometer (OFV-3001/303) and a laser sensor (LK-2101/081), respectively. The flapping and morphing motion of the wing throughout the entire wing-stroke is analyzed by the use of a high speed camera (IDT XS-3).

The aerodynamic tests are conducted in a subsonic wind tunnel with a test section of 1 m x 0.75 m x 2.2 m for various flight conditions according to wind speeds from 5 to 12 m/s, the flapping frequency from 2 to 12 Hz and the incidence angle of the flapping axis from -20 to 50 degrees. The actuation frequency is equal to the flapping frequency, and three input parameters, DC offset value, amplitude and phase of the input signal, are controlled to generate the maximum lift drag ratio for each flight condition. From the results, the relationship between the flight conditions and the modification of the wing surface is discussed, and this result is useful for deep understanding of the flapping flight.

6173-17, Session 4

Design, fabrication and testing of energy-harvesting thermoelectric generator

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Hi-Z Technology Inc. is currently performing the Navy program in which it is using its thermoelectric generator (TEG) technology in designing and fabricating a prototype small energy-harvesting device to provide power for shipboard health-monitoring wireless sensors and data transmitters. The TEGs utilize the heat transfer between shipboard waste heat sources and the ambient air to generate electricity. In order to satisfy the required small design volume (one cubic inch), Hi-Z is using its innovative multi-layer thin-film Quantum Well thermoelectric technology that will provide a factor of four increase in the conversion efficiency and a large reduction in the design volume over the SOTA bulk Bi2Te3 based thermoelectics. Quantum Wells (QW) are nanostructured multi-layer films. The wireless sensors can be used to detect cracks, corrosion, impact damage, and vibration and temperature excursions as part of the Condition Based Maintenance (CBM) of the Navy ship machinery. The CBM of the ship machinery can be significantly improved by automating the process with the use of self-powered wireless sensors. These energy-harvesting TEGs can be used to replace batteries as electrical power sources and to eliminate tethered wires. It is planned to test the prototype QW TEG in a simulated thermal environment, and later in the actual ship's environment.

6173-18, Session 4

Sliding mode control of a spherical haptic device featuring electrorheological fluid

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This paper presents force feedback control performance of a new type of haptic device featuring spherical geometry and smart materials that can be used for minimally invasive surgery (MIS). A spherical electrorheological (ER) joint is designed and optimized based on the mathematical torque modeling, and then torque response of the manufactured ER joint is experimentally evaluated. This spherical ER joint adopting clutch mechanism can ensure mechanically safety for medical application. Furthermore, it can guarantee the improved control performance and the easy realization of multi-dimensional force feedback. Subsequently, the 2-DOF force feedback device is manufactured by integration the spherical ER joint with AC motor. In order to achieve desired force trajectories of the haptic device, a sliding mode controller which is robust to uncertainty is formulated after hysteretic behavior of the ER fluid is investigated as uncertainty. The controller is experimentally realized. Tracking control performances for various force trajectories are presented, and their tracking errors are evaluated in time domain.

6173-19, Session 5

Design and fabrication of PPy-Carbon micro-electromechanical switches

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A process has been developed to fabricate suspended carbon-microelectromechanical systems (C-MEMS) structures integrated with polypyrole for micro-switch applications. The fact that suspended micro/nano structures are free of Van-der-waal's interactions with the substrate makes them interesting for integration in mechanical, electrical, and electromechanical measurements.These suspended micro/nanostructures have the potential to enable revolutionary technology for sensing, actuation, computing and information technology[1]. The role of polymer materials used as part of the MEMS structural materials obtains certain advantages like flexibility and biocompatibility of these structures which allow us to use them in electronic applications and biotechnology field [1]. SU-8, a negative photoresist, was used as the starting material and was converted to desired C-MEMS structures using pyrolysis in an inert atmosphere [2-4]. The suspended carbon-micro/nano electromechanical systems (C-MEMS/NEMS) structures were fabricated by Ultra Violet (UV) /Electron Beam (EB) lithography and pyrolysis method. The problem of charging of the non-conductive substrate was solved by partially masking a thin metal layer before EB writing the suspended structures. Polypyrole was uniformly grown on these suspended carbon microstructures with these structures acting as a backbone for the growth of the polypyrole layer. When

a DC electrostatic field is applied to the lower electrode causing the formation of positive and negative charges on the electrode and conductor surfaces, these charges exhibit attractive forces which cause the suspended C-MEMS/PPy structure to snap down on to the lower electrode causing mechanical contact with the ground. We study the pull-in voltage characteristics of the C-MEMS-PPy suspended structures with a metal ground electrode. Since PPy is well know for its flexible nature with a Young's Modulus of around 0.2GPa, it is believed to be more reliable than the metal-MEMS switches.

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6173-20, Session 5

Smart impact management devices: experimental validation of crash triggered rapid expansion of aluminum honeycomb

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A major limitation of current dedicated crash energy management structures and passive occupant protection devices such as interior padding used in the transportation industry is that their starting volume is their maximum volume, i.e. they dissipate energy by crushing or stroking from a larger to a smaller volume. Since they occupy their maximum volumes in their uncrushed-as-installed state they occupy space that is then only functional in crash and is otherwise wasted. Expressed another way, space is dedicated to such devices throughout the life of the vehicle even though a severe crash may actually occur only once during that time span. This space so occupied is not available for other uses, including such necessary/desirable functions as vehicle serviceability and repair, operational clearances, and interior spaciousness. This limitation has led to the proposal of a class of "smart" energy management and occupant protection devices, based on unexpanded aluminum honeycomb (HOBE), that initially occupy a small volume and based on sensor input are rapidly expanded to a much larger crushable volume just prior to or in response to a crash. Energy management/occupant protection devices based on this technology, should it prove to be viable, would thus allow empty space to be left adjacent to them for operational clearances, serviceability and repair functions, etc. which spaces would yet be fully utilized, due to the expansion of the device, for crash energy management/occupant protection. This paper documents the first portion of an exploration of the viability of this technology, specifically validation of feasibility through in-lab testing. Analysis and design portions are to be documented in separate papers. Specific goals of the here-in documented test program were the demonstration, starting from blocks of unexpanded aluminum honeycomb, a) of the feasibility (and robustness) of sensor triggered rapid expansion both in terms of the integrity and uniformity of the resulting expanded honeycomb, b) that expansion mechanisms that were required could be simple and have low energy/force requirements, and c) that the after expansion crush response of the rapidly expanded honeycomb is comparable to that of the standard pre-expanded commercial product. The test program documented here was successful in all respects, demonstrating and thus validating the feasibility and robustness of this new proposed technology of crash triggered deployable aluminum honeycomb. Specific findings were as follows:

- feasibility (and robustness) of rapid expansion was demonstrated both in terms of the integrity and uniformity of the resulting expanded honeycomb
- rapid expansion was robust to the upper limit of the available expansion rate/time: 15 m/s, 16 ms
- the expansion ratio needed to achieve uniform honeycomb cell structure was between 50 to 60
- equations were established and validated for the required starting thickness of HOBE
- rapid expansion was robust, with no loss of integrity for expansions from between 0.5 to 1.5 times that which is required to achieve the hexagonal cell structure of the commercial pre-expanded product
- 7-8 repeated expansions could be performed cyclically on the same specimen before the cell structure began to breakdown

6173-21, Session 5

Resonant operation of a piezohydraulic actuator

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Piezohydraulic actuators are a new frontier in the search for small scale, high power devices; currently exhibiting a specific power density (W/kg) on the order of 150 W/kg. The ability to operate a piezohydraulic actuator at its resonance frequencies would further open industrial markets to the application of such actuators. In this work, a high frequency (i.e., 10 kHz), high flow rate (i.e., 20 cc/s) passive check valve has been integrated into a Piezohydraulic Pump. The initial and final configurations are compared. Special attention is paid to the maximum available operating frequency in each configuration, as well as the maximum flow rate and power output. The expected results are that by increasing the available operating frequency by a factor from 1 kHz to 10 kHz, the flow rate will increase from approximately 17 cc/s to 170 cc/s. Similarly, the power output should increase from 42 W to 420 W, increasing the specific power from 150 W/kg to 1500 W/kg, with no increase in volume or mass. Additionally, the Piezohydraulic Pump is operated at its resonance frequency and the results discussed.

6173-22, Session 5

Resonance-based low-frequency synthetic jet actuator modeling, design and testing

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Synthetic Jet Actuators have been the topic of extensive study in the aerospace industry because of their ability to actively control flow over aerodynamic surfaces without discrete control surfaces such as a flap. One challenge had been to develop a low frequency, lightweight actuator that can provide large displacements. This paper will discuss the modeling, design, manufacture, and testing of a bimorph piezo-composite actuator that will provide such displacements at low frequencies. The design employs two opposing benders that provide a piston-type motion. The bender is created by separating a piezo into three segments and then actuating the two end segments 180 degrees out of phase with the middle segment. When two of these benders are actuated out of phase a recurve actuator is created.

The actuator is built by sandwiching a piece of 6-mil carbon fiber prepreg between two 10-mil piezos. The actuators are 1⁄2" x 3" in size. In addition, a thin strip of fiberglass fibers combined with conductive epoxy spans the length of the piezo. This provides added strength and helps keep the piezos from cracking when they are actuated. Once the carbon prepreg is cured a thin strip of electrodes is etched off at 1⁄4 and 3⁄4 lengths. The piezos are then mounted and connected to the piston

Air velocity, blocked force and displacement data were collected using a pressure sensor, a load cell and a laser displacement sensor respectively. Initial tests of this recurve actuator using Rockwell Scientific PLZT-98 high energy density piezos produced +/- 45 mils displacement and 30 m/s air flow out of the chamber. These tests were run at 200 volts peak to peak and 120.4 Hz, the resonant frequency of the system. Subsequent displacements and velocities measured using the PLZT-98 were twice that of the recurve actuators built using standard PZT-5A.

Current work includes the development of a dual recurve actuator. For this configuration two recurves (i.e. four piezo benders) are run are of phase, one on each side of a duel action piston. Velocity outputs in the range of 50 to 60 m/s are expected for this set-up. In order to ensure that the two actuators are running at the same resonant frequency, each recurve will have a thin threaded rod with a bolt on either end. The bolts will be tightened in order to slightly change the stiffness of each actuator until the resonant frequencies are matched. Once the dual actuator is built and tested and a nominal actuator/piston/chamber size configuration is determined the actuator will be put into a wind tunnel so that crossflow interactions can be analyzed. The connector to the wind tunnel has been designed such that the nozzle width, thickness, and angle can all be altered in order to determine which configuration gives the most effective results.

6173-23, Session 5

System-based approach for an advanced drug delivery platform

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Present study is looking at the problem of integrating catheter (guiding system), drug delivery microcapsule and a bio-sensor into a biomedical system. A wide range of medical practices from cancer therapy to gastroenterological treatments can benefit from such novel bio-system.

Drug release in our drug delivery system is achieved by electrochemically actuating an array of polymeric valves on a set of drug reservoirs. The valves are bilayer structures, made in the shape of a flap hinged on one side to a valve seat, and consist of thin films of evaporated gold and electrochemically deposited polypyrrole (PPy). These thin PPy(DBS) bilayer flaps cover access holes to underlying chambers micromachined in a silicon substrate. Chromium and polyimide layers are applied to implement “differential adhesion” to obtain a voltage induced release of the bilayer from the drug reservoir. The Cr layer is used as an adhesion-promoting layer, which is used to “glue” the Au layer down, whereas the gold adheres weakly to polyimide. Drug actives (dry or wet) were pre-stored in the chambers and their release is accomplished by bending the bilayer flaps away from the substrate with a small applied bias (~ 1V) due to ion movement inside/outside of the polymer.

Charge density of 102mC/cm2 has been calculated to actuate these PPy(DBS) valves. Compared with charge density of 450mC/cm2 needed in a drug delivery system based on Au corrosion, our device consumes 75% less energy per unit area to open the drug reservoirs. Multiple-drug pulsatile release and continuous linear release patterns can be implemented by controlling the activations of an array of valves. Varying amounts of drugs, together with more complex controlling strategies would allow creation of more complex drug delivery patterns.

This design of the drug delivery module is miniaturized to the dimensions of 200μm valve diameter, for this device to be integrated with commercially available catheters (with outer diameter of 1mm).

Catheters of varying sizes are used for minimally invasive surgeries. The modern catheters are capable of performing multiple electro physiological functions. Foley catheters are still used for basic functionality of insertion into urinary bladder for drainage of urine. Others are used for their advanced features such as three dimensional mapping of heart, or tissue ablation. Steerable catheters could be flouroguided or could be equipped with optic fiber for visualization. One such type of visualization catheter is being used for detection of breast cancer at an early stage.

These steerable thin catheters can be used to position our drug delivery capsule for release of highly toxic medicine at the infection site, for maximum effect and minimum side-effect.

6173-24, Session 6

Modeling approaches for active systems

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To solve a wide range of vibration problems with the active structures technology, different simulation approaches for several models are needed. The selection of an appropriate modeling strategy is depending, amongst others, on the frequency range, the modal density and the control target. An active system consists of several components: the mechanical structure, at least one sensor and actuator, signal conditioning electronics and the controller. For each individual part of the active system the simulation approaches can be different. To integrate the several modeling approaches into an active system simulation and to ensure a highly efficient and accurate calculation, all sub models must harmonize.

For this purpose, structural models considered in this article are modal state-space formulations for the lower frequency range and transfer function based models for the higher frequency range. The modal state-space formulations are derived from finite element models and/or experimental modal analyses. Consequently, the structure models which are based on transfer functions are directly derived from measurements. The transfer functions are identified with the Steiglitz-McBride iteration method. To convert them from the z-domain to the s-domain a least squares solution is implemented.

An analytical approach is used to derive models of active interfaces (actuators). These models are transferred into impedance formulations. To couple mechanical and electrical sub-systems with the active materials, the concept of impedance modeling was successfully tested. The impedance models are enhanced by adapting them to adequate measurements.

The controller design strongly depends on the frequency range and the number of modes to be controlled. To control systems with a small number of modes, techniques such as active damping or independent modal space control may be used, whereas in the case of systems with a large number of modes or with modes that are not well separated, other control concepts (e.g. adaptive controllers) are more convenient.

If other elements (e.g. signal amplifiers or filters) in the signal paths have a significant influence on the transfer functions, they must be modeled as well by an adequate transfer function model.

All the different models described above are implemented into one typical active system simulation. Afterwards, experiments will be performed to verify the simulations.

6173-25, Session 6

Adaptive hysteresis compensation in trajectory control of piezoelectrically-driven nanostagers

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Complex structural nonlinearities of piezoelectric actuators drastically degrade their performance in variety of micro- and nano-positioning applications. From the precision positioning and control perspective, the multi-path time-history dependent hysteresis phenomenon is the most concerned nonlinearity in piezoelectric actuators to be analyzed. Along this line, this paper undertakes the developments of a nonlinear modeling and control framework for piezoelectically-driven stagers. More specifically, the hysteresis phenomenon is modeled using some structured polynomials with unknown time-varying coefficients for the rising and descending hysteresis curves. Utilizing the properties of turning points and the configuration of the loading curves, a novel algorithm for identification of the coefficients of the hysteresis polynomials is developed. A second order linear dynamic is then combined with the proposed nonlinear hysteresis model to more accurately describe the real stager dynamics.

A charge-based backstepping feedback control framework is then used to control the nanostager position despite the parameters uncertainties in the proposed hysteresis model. Numerical simulations demonstrate the feasibility of the controller. Various experiments have been carried out to validate the theoretical developments and demonstrate the controller performance for an in-house Physik Instrumente P-753.11c nanolanipulator with high resolution capacitive position sensor feedback. Trajectory tracking of the actuator is investigated for low and high frequency harmonic commands. Both numerical simulations and experimental results indicate that controller suppresses the high frequency tracking error significantly, noticeably improving the tracking performance.

6173-26, Session 6

Piezoelectric generator based on 15 shear mode for vibration power scavenging

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In this paper, a new piezoelectric generator operating in “15” shear mode is first developed to scavenge the vibration power from its host structure. The proposed device is designed to have a cantilever beam with a PZT layer on top and a seismic mass added to the end, the electrode is patterned into an interdigital shape on top of the PZT layer in order to employ the “15” mode of the piezoelectric effect. This “15” mode design generates more than 30 times higher voltage than that of the conventional “31” mode design of the same configuration. An equivalent circuit model of this mechanical-electrical system is established and then the output performance is investigated by electric circuit analysis methods. A power triangle concept is adopted to analyze power optimization and power distribution of the generator with resistive load. Furthermore, an ultra-capacitor is first employed to store the scavenged energy and its energy storage characterization is also discussed and optimized. Then both numerical simulations and experiments are examined to verify the model. At last, some design guidelines and optimization consideration are presented based on the model.

6173-27, Session 6

Adaptive frequency regulation of active probes for mass sensing applications

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Microcantilever-based sensors have recently generated tremendous interest because of their ability to detect a wide range of physical, chemical and biological agents with high sensitivity and low costs. Presence of matter particles changes the natural frequency of microcantilever by a small but detectable amount. This forms the basis of the dynamic mode of operation for mass sensing applications. Several techniques such as optical, piezoresistive, piezoelectric and capacitive are being utilized to detect changes in the microcantilever frequency, which could reveal the particle mass. Such techniques give accurate results in vacuum, however the performance degrades considerably when they are operated in air. This is often attributed to decrease in the Q factor because of increase in the ambient noise levels. Several techniques such as amplification of microcantilever vibrations through feedback control, measurement of higher order modes of resonance, measurement of torsional, lateral modes of resonance and use of parametric resonance have been proposed to increase the sensitivity in air by enhancing the Q factor.

This paper proposes the development of an adaptive controller for microcantilever-based mass detection by treating this as a frequency regulation problem. A piezoelectric layer deposited on the microcantilever surface can be used for both actuation and sensing. The frequency of vibration, shifted due to the presence of mass, will then be regulated back to the reference frequency using feedback control. Mathematical models describing the dynamics of microcantilever beam and the self-sensing piezoelectric patch are presented. The control problem comprises of regulating the piezoelectric actuator voltage in the presence of unmodeled dynamics (e.g., air damping) and parameter uncertainties. Feasibility of the theoretical developments will be experimentally validated using a commercially available active probe appended on an in-house nanomanipulator platform.

6173-28, Session 6

Thrust vector control of satellites using smart parallel manipulators

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The ability to control thrust vector of any spacecraft propulsion system is extremely advantageous and decisive to the spacecraft performance. For satellites, the thrust vector of thruster should ideally pass through the mass center of a satellite to avoid the satellite rotating out of its orbit. In reality, there is a tolerance on this alignment that consequently results in a disturbance torque. To counter the effects of this disturbance torque in the presence of a large thrust level, either the space vehicle should be spun in the opposite direction by employing auxiliary thrusters or a means of controlling the required thrust orientation has to be provided. In general, gimbals are used as a means of reorienting the thruster in the intended thrust direction to provide coarse position correction for thrust alignment. However, this usually imposes a significant mass penalty. In addition, small thrusters in the so-called reaction control systems (RCS) are currently used in satellites to correct the thrust vector misalignment. The use of the RCS obviously adds additional mass to satellites and consumes additional satellite fuel thus shortening the lifetime of satellites.

This paper presents the concept, control strategy, and simulations of thrust vector control of satellites using the UHM (University of Hawaii at Manoa) smart parallel manipulator. The UHM smart parallel manipulator provides a novel technical means of satellite thrust vector control (TVC). This manipulator is an intelligent composite platform with simultaneous precision positioning and vibration suppression (SPPVS) capabilities, and can provide two degrees of rotational freedom for the top device-plate on which the satellite thruster is mounted. The new concept of satellite TVC simplifies the TVC system, changes the driving energy of the TVC system from onboard fuel to electricity from solar panels, and adds the vibration suppression capability to the satellite. The design, positioning capability, and vibration suppression capability of the manipulator have been investigated before. This paper focuses on the satellite TVC system design, analysis, and simulations. First, the innovative TVC concept is introduced, which utilizes the UHM multifunctional smart parallel manipulator to provide precision position control of the thruster vector and vibration suppression capability while the thruster fires. The configuration of the thrust vector control system is then illustrated, and the satellite attitude dynamic model for thrust vector control is built. Next, the UHM smart parallel manipulator is introduced and its kinematics and controller design are discussed. The fuzzy logic controller is employed to precisely position the smart parallel manipulator and to compensate the non-linearities due to the friction and backlash of the actuators and the tolerance of joints. Finally, the satellite attitude controller and the fuzzy logic controller are designed, and simulations are carried out to realize the thrust vector control of a satellite. The results indicate that the smart parallel manipulator can precisely achieve the thrust vector control, the misalignment of the trust vector of the satellite can be corrected effectively, and the position accuracy of the thrust vector is 0.68 arc minutes.

6173-29, Session 7

Design of piezoelectric shunt structures using admittance analysis

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Piezoelectric material has the ability to transfer mechanical energy to electrical energy and many researchers have studied passive damping of mechanical vibration/noise using piezoelectric shunt system based on this property. The mechanism of piezoelectric shunt system can be divided into two part, first, energy transfer from mechanical system to electrical system, and second, dissipating the transferred electrical energy in shunt circuit. To dissipate mechanical energy efficiently, mechanical energy in the piezoelectric structure must be transferred cost effectively to electrical energy. Therefore, the analysis of electro-mechanical characteristics of piezoelectric structures is very important for the design and prediction of performance in piezoelectric shunt system.

In this paper, admittance will be introduced to represent electro-mechanical characteristics of piezoelectric structures and to predict the performance of piezoelectric shunt system. It will be shown that admittance in open circuit is proportional to dissipated energy in the shunt system. After that, admittance will be used as a design parameter in the piezoelectric shunt system and be obtained using finite element method. The obtained admittance will be validated by experiment. Vibration reduction of the piezoelectric structure with shunt circuit will be realized by experiments. Damped system response of piezoelectric structure in frequency and time domain will prove that admittance is proportional to the performance of piezoelectric shunt system. Therefore, a new design method of piezoelectric shunt system using admittance analysis is expected to save design cost of the piezoelectric structure.

6173-30, Session 7

Vibration control with adaptive structures

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The mission of the Fraunhofer Gesellschaft is to identify technologies with a high impact potential for commercial applications and to take all necessary steps to successfully promote them by performing cooperative industrial research activities. One such technology is smart structures, known as adaptive structures in German. Most recently, Fraunhofer decided to strategically extend its portfolio to include this technology and summarize its R&D activities in the FIT (Fraunhofer Innovation Topics) Adaptronics. To improve Fraunhofer's competencies in adaptronics, especially with respect to system design and implementation, the Fraunhofer internal project MAVO FASPAS was launched in 2001. Now, after almost 3 years of work the project is approaching its end. The presentation will discuss major project results.

The project is divided into different work areas that can be roughly identified as 1.) design, procurement and characterization of advanced piezoceramic actuator and sensor subsystems, whereas the latter are equipped with miniaturized, integrated signal conditioning electronics, 2.) development and verification of methods to assess the reliability of adaptive systems, 3.) development of a systematic approach for integrative simulation of controlled active systems, 4.) control engineering for different AVC systems with a special focus on controller coding and implementation in embedded systems. The progress and results in the different subprojects are assessed by designing and commissioning 3 different active systems for AVC for both automotive and machine tool technology. Two of these systems can be characterized as active interface structures which base on the integration of discrete actuator systems whereas the third is an active strut with two-dimensional actuators.

The actuator work ranges from modeling to realization of piezo multilayer actuator array structures as well as of two to three dimensional piezo components. Especially the new 3D-actuator composites feature a high robustness against mechanical loads. The sensor work focuses on exploiting both PZT thin layers and thin fibers and progress the packaging technology to semi-finished strain sensor modules. Specific charge amplifier circuits are developed, miniaturized and integrated into the sensor modules to realize two types of sensor systems. Furthermore, one important goal is to establish a system simulation approach that integrates the most suitable engineering design methods and tools for active system design and assessment. This covers both numerical and experimental approaches and ranges from FEA and MBS to CACE. The control engineering gives a special emphasis on implementing the controller code on embedded systems to ensure a possible low cost system design whereas microcontrollers, DSPs and FPGAs are covered. For this, Fraunhofer's high level language SynERJY is being investigated. Furthermore, an approach to assess the reliability of such smart systems is being developed based on know-how on mechanical durability of passive structures. All afore mentioned R&D-topics are validated and continuously refocused by the work with the three demonstration structures are 1.) an active high load interface for an automotive suspension strut - to control the vibration transmission into the car body -, 2.) an active screw drive within a machine tool - to control the mechanical restraint and reduce slackness - and 3.) an active strut of a tripod machine tool - to control torsional and bending vibrations of the tool holder.

6173-32, Session 7

Wrinkling control of inflatable booms using smart material patch

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Inflatable boom is a fundamental structural part of inflatable space structures such as in antenna, sunshield, and solar sail applications. After the appropriate deployment, this structural part maintains the expected configuration of the whole system, supporting external loads and affecting the efficiency of the membrane surface. However, the membrane structures can be easily distorted and even collapsed by wrinkling which can be generated by many different reasons such as material property deterioration, thermal effect, heavy load, and vibration. The numerical and experimental studies to reduce adverse effects of wrinkling in the inflatable structures using smart material patch is performed in this research.

Finite element model of inflatable boom structure is constructed using membrane element supported by ABAQUS. To simulated wrinkling phenomenon, the numerical algorithm of wrinkling based on Miller-Hedgepeth membrane theory is developed using user material (UMAT) subroutine written by FORTRAN. Wrinkled pattern and deformed shape of inflatable boom structures are investigated using ABAQUS with UMAT subroutine of wrinkling algorithm.

The experimental inflatable boom models made of Tedlar film are 1m in length with various diameters. The bending tests are performed with different internal pressures. The deformed shape of boom structure is observed globally and locally by laser sensor and digital camera. At each load step, two different types of pictures are taken for observing the wrinkling pattern and propagation, one is taken far from about 1m distance to observe global deformation and the other is taken very close to root of the boom where the wrinkles are mainly generated as can be expected. Using photogrammetry, 3D positions of several points of boom are calculated at each load step as well as wrinkled direction and area.

Numerical results are compared with experimental bending tests. The results show that this numerical model with wrinkling algorithm is useful to expect not only the global deformed shape and the advent of wrinkles but also wrinkling area and patterns. From the numerical and experimental results, it is found that the inflatable structural performance critically depends on internal pressure, slenderness, material properties, and outside environmental condition.

As the wrinkling region increases, the structural performance of inflatable boom is rapidly deteriorated. Therefore, the growth of wrinkling should be avoided during the operation. The patch type thin film actuator and tendon system is applied to reduce adverse wrinkling effects such as debasement of load carrying capacity or position accuracy, and collapse of the structure. The prototype of this system uses Macro Fiber Composite (MFC), which is a kind of piezoelectric thin film developed by NASA. As MFC provides high force and flexible surface, it is used to prevent the tendon frame to move and hold the entire structure as we expect. After applying this control device, the load limit that the inflatable boom can sustain is extended and the nonlinear behavior near wrinkling load point is improved. The credible numerical model will be verified by experiments and the methodology for overcoming wrinkling with smart patch is demonstrated in this research.

6173-33, Session 7

Adaptive rectangular membranes actuated near boundaries

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This paper discusses work relevant to small membrane-based lightweight adaptive fast steering mirrors with applications in space communication. The deformability of membranes can in theory be utilized to drive the mirror in higher order modes such as defocus, coma, and astigmatism; in addition to the frequently available tip and tilt modes. However, proper control of the actuation sequence is necessary if the higher modes are to be effected accurately and reliably. This work is also relevant in that the membranes are here driven only by a small number of actuators adjacent to the boundary, which could possibly address issues such as "print through" that could otherwise arise in thin-film mirrors.

Considerable work exists in the literature on adaptive optics and wavefront control. Applications of fast steering mirrors include, for example, implementation in a closed-loop control system designed to minimize laser beam distortion due to acoustic noise in an aircraft (Glease et al., 2000). Additional applications such as laser beam scanning have also been pursued, and fast steering mirror hardware is also commercially available through, for example, PhysikInstrumente and Ball Aerospace (Physik Instrumente, 2004; Ball Aerospace, 2004). To bring down costs and further reduce weights, recent attention has been directed at using MEMS technology to make deformable thin-film mirrors driven by electrostatic actuators (Bush, 2004).

This work also uses electrostatic actuators, which are direct-written on the membrane and the stationary base using a relatively low cost Maskless material deposition process. In addition, as mentioned, the actuators are located strictly adjacent to the clamped boundary, and the goal has been to use the minimum number required to produce the desired deformation modes. This paper investigates the relationship between the number of actuators to produce 2 or more deformable modes in addition to tip and tilt and the speed of actuation for a particular mode for a small rectangular membrane. Also investigated is the role membrane tension plays in determining actuation speed and the modes excited, and its possible use as a control parameter to provide adaptivity to the membrane mirror dynamics. Analytical solution is based on a Green's function formulation. A Kapton membrane is used in the experiments, and measurements are made using a laser vibrometer. Analytical results so far point to some limitations on how well all of the required modes may be achieved by a given number of boundary-adjacent actuators over a wide frequency band.

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6173-34, Session 7

Theoretical investigation of 2D plate structure excited by patches of piezoelectric actuators

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Interest in the use of smart-structure technology for noise and vibration reduction in several applications has been on the rise in recent years. It has been established that significant gains in structures performance can be achieved through active vibration control.

In this study a two dimensional theoretical vibration analysis for thin plate structures excited by patches of piezoelectric actuator is presented. To investigate the influence of actuator location and configuration of single and multi patches of piezoelectric actuators attached to the plate surface in order to determine the optimal location and configuration of the piezoelectric actuators for selective modal excitation. In addition, the bonding layer thickness influence is included in this

analysis. The classical thin-plate theory is used in the study to derive the equation of motion for the plate structure excitation by patch type of piezoelectric actuators. Single and multi-actuator configurations are considered in this analysis. The results demonstrate that the input excitation frequencies are markedly affects the modal responses of the plate structure where actuators are properly located. However, at off- resonance the modal distribution depends upon the actuator location and configuration. So that, it is important to select actuator location carefully in order to dampen the vibrations of the plate at these resonant frequencies leading to improve control behaviour. Moreover, multi actuator configuration has an influence on the plate structure, will provide better excitation than single actuator configuration.

6173-62, Poster Session

Modeling actuation forces and strains in Nastic structures

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Nastic structures are capable of three dimensional shape change using biological principles borrowed from plant motion. The plant motor cells increase or decrease in size through a change in osmotic pressure. When nonuniform cell swelling occurs, it causes the plant tissue to warp and change shape, resulting it net movement, known as nastic motion, which is the same phenomena that causes plants to angle their broad leaf and flower surfaces to face light sources.

The nastic structures considered in this paper are composed of a bilayer of microactuator arrays with a fluid reservoir in between the two layers. The actuators are housed in a thin plate and expand when water from the fluid reservoir is pumped into the actuation chamber through a phospholipid bilayer with embedded active transport proteins, which move the water from the low pressure fluid reservoir into a high pressure actuation chamber. Increasing water pressure inside the actuator causes lateral expansion and axial bulging, and the net volume change of actuators throughout the nastic structure results in twisting or bending shape change. Modifying the actuation displacement allows for controlled volume change. Modeling the driving and blocking forces involved in actuation, as well as stress and strain that occurs due to the changing pressures, is done analytically. Actuation is driven by increasing osmotic pressure, and blocking forces are taken into consideration to plan actuator response so that outside forces do not counteract the displacement of actuation. Nastic structures are designed with use in unmanned aerial vehicles in mind, so blocking forces are modeled to be similar to in-flight conditions. Stress in the system is modeled so that any residual strain or lasting deformation can be determined, as well as a lifespan before failure from repeated actuation. The long-term aim of our work is to determine the power and energy efficiency of nastic structures actuation mechanism.

6173-63, Poster Session

Sub structure on-line tests on braced frames with self-returning joint mechanism

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Many researchers are studying on possibilities of various kinds of new media, new material, and new devices to make a structural system more smart/intelligent. Among them, this paper deals with shape memory alloy, abbreviated as SMA. This alloy exhibits different properties depending on temperature; such as 1) shape memory effect, 2) pseudo-elasticity, and 3) transitional state between them. While this kind of alloy has been already used in many aspects in everyday life, only few practical applications are found in structural system itself. Here, in order to assess the applicability of this kind of alloy in structural system, a flush type endplate connection at beam-ends is arranged by use of SMA bolts.

Because of luck of practice, a constitutive modeling of this alloy suitable for structural analysis is not yet established. In such a situation, a pseudo-dynamic response test is useful to study the non-linear behavior during earthquake, because this technique does not require a mathematical constitutive modeling of structural elements. Considering the present cost performance of this alloy, very limited amount can be used in a structural system. Then most portion of the whole structural system must be made of ordinary construction materials, the behavior of which has been already well known. For such a reason, this paper applies a substructure pseudo-dynamic test technique to a hybrid model of structure, where only an element made of this alloy is chosen as a specimen and the remaining portions are fictitious or only exist in computer memory. Furthermore, the seismic behavior of SMA bolt connection is simulated by a mathematical model of the moment vs. joint rotation curve, and the results of numerical simulation are compared with the test results.

6173-64, Poster Session

Development of active CFRP/metal laminates and their demonstrations in complicated forms

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The present paper describes development of high performance CFRP (Carbon Fiber Reinforced Plastics)/metal active laminates which can work as actuating panels only bend in the fiber direction driven by electric resistance heating of the carbon fiber. The development was undertaken mainly by investigating the effect of kind and thickness of the metal layer on their deformation characteristics. Various types of the laminates were made by hot-pressing of an aluminum, an aluminum alloy, a magnesium alloy, a stainless steel, a titanium or a zinc plate for the metal layer as a high CTE (Coefficient of Thermal Expansion) material, a unidirectional CFRP prepreg as a low CTE and electric resistance heating material, and a unidirectional KFRP (Kevlar Fiber Reinforced Plastics) prepreg as a low CTE and insulating material. The main results obtained in this study are as follows: (1) Performance of the active laminate under constant thicknesses of the CFRP and KFRP prepregs kept at mono-layer were examined and it was found that the pure aluminum, the aluminum alloy and the magnesium alloy realized a high level and unidirectional actuation, and the stainless steel realized actuation a little less than the level and unidirectional. (2) The effect of the CFRP and the aluminum thicknesses on the curvature of the active laminate at 313 K was investigated and it became clear that its dependency on both of the layers are similar, so that various combinations of their thicknesses can be selected to obtain a certain curvature. (3) The output force generated by the active laminate made by using the aluminum or the aluminum alloy plate of various thickness increased with increasing the thickness and by selecting the aluminum alloy which maintained a linear increase up to a higher temperature range and attained a higher value because of its higher yield stress compared with the pure aluminum. (4) The active laminates were made into complicated forms such as hatching, stacking, coiling and lifting types, and various actuation performances were successfully demonstrated.

6173-65, Poster Session

Theory and design methodology for synthesis of adaptive and distributed compliant systems with embedded actuation

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Electromechanical systems are generally comprised of separate, nearly rigid components, with relative motion occurring at discrete locations, e.g. joints. In contrast, many designs in nature develop as one connected whole, with flexure distributed throughout the material. In particular, 90% of all living creatures, the invertebrates, rely on compliance for motion and force transmission. Compliant mechanisms are a relatively new class of mechanisms that use engineered elasticity of the constituent elements to transmit motion and/or force. Since flexure is permitted in these mechanisms, they lend themselves to integration with unconventional actuation schemes including thermal, electrostatic, piezo-electric, artificial muscle, and shape-memory-alloy actuators. The design methods and the applications of compliant mechanisms apply to many problems in micro, meso, and macro domains.

To build a strong link in the bridge between compliant mechanisms and adaptive structures, we are now automating the synthesis of compliant systems, defined as joint-less monolithic mechanisms embedded with actuators and sensors. We have developed methods for optimal topology, size, and shape of monolithic elastic mechanisms with integrated synthesis of sensors and actuators, for maximum energy efficiency and adaptive performance. The research lays a mathematical framework for systematic synthesis of multifunctional designs by addressing the issues fundamental to distribution of components within a compliant active structure. With actuators and sensors now treated as variables during synthesis, they can determine structural topology rather than be determined by it.

We investigate basic research issues including (i) optimal layout of the structure, actuators, and sensors and (ii) the groundwork for embedded controls in compliant mechatronic systems. A generalized synthesis scheme is formulated in which the design requirements are captured in a mathematical form to transform an initial grid of elements into an optimal layout of elastic beams, sensors, and actuators. Genetic algorithms are employed for their ability to find global optima for discrete, nonlinear problems. In addition, the actuators are mathematically characterized by their operational load-deflection curves and active stiffness, in contrast to the practice of simple point-load representation.

Our general approach to integrate controls with compliant mechanisms is not to optimize the controller, but to optimize the controllability characteristics of the system. Controllability and observability of the structure are defined in terms of the linear independence of the actuators and sensors, and are incorporated into the optimization. The general idea is that if the actuators independently effect the output displacement, then they can compensate for a variety of unknown and arbitrary loading conditions.

Results for both single and multi-actuator synthesis are presented herein. Example problems were selected from benchmark problems in compliant mechanism design. Convergence required modification of the genetic algorithms and implementation of graph searches to guarantee structural connectivity. The broader impacts of the research are: (i) high performance designs of several products ranging from autonomous robots, surgical instruments, adaptive wings, structural health monitoring systems, and adaptive orthoses, and (ii) advancement of smart structures to the next level of sophistication by creating monolithic systems with embedded-and-distributed sensing and actuation, in contrast to individually designed structures, actuators, and sensors.

6173-66, Poster Session

Design and experimental characterization of flexure activated by SMA-wires for microassembly operations

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This paper reports a design SMA-Flexure system dedicated to operations of Microassembly. The concept design employs a Flexure-stage with 3 degree-of-freedom (3-DOF) planar motion and SMA wires. The Flexure-stage was designed to reduce the input displacement of the SMA wires; therefore the output displacement has a higher resolution of motion. Detailed analysis of the mechanics and design of the SMA-Flexure system are covered, and preliminary experimental results verifying the basics operational principles of the design concept are reported. The control strategy is implemented using a dSPACE real-time control system.

6173-35, Session 8

Biologically inspired anthropomorphic arm and dextrous robot hand actuated by smart-material-based artificial muscles

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Shape memory alloys (SMA) are a class of smart material having the unique ability to return to a predefined shape when heated. SMA based actuators have the potential to be very compact and low weight. As a result, much research has been devoted to the design of SMA based actuators; however, commercialization has been largely impeded by the small strain capacity inherent to SMA. To address this deficiency, this paper conveys the design of a large-strain SMA actuator (\>30%) whose feasibility is investigated by integrating the actuators as artificial muscles in a two link anthropomorphic arm. The ensuing experimental results indicate that the actuators show great potential for a variety of emerging applications. Finally the design and evaluation of an SMA based dextrous robotic hand is presented, and provides a case study illustrating how smart structures provide a superior alternative to conventionally voluminous and heavy prosthetic actuators.

6173-36, Session 8

Galfenol tactile sensor array and visual mapping system

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A tactile sensor system that mimics the human ability to feel in both resolution and force levels can be used to produce a visual map of objects or surfaces producing the force(s). Thus far, technology has not been able to construct such a sensor system that can provide this level of capability in an acceptable package. Using the smart material Galfenol, a lightweight, low volume, and high resolution tactile sensor can be constructed. Many applications exist in the robotic and medical fields for these sensors with these capabilities.

Galfenol is a magnetostrictive material that exhibits a useful permeability change when subjected to mechanical stresses. When placed within a magnetic field, the force applied to the material can be measured as related to the change of flux flowing through the material. Galfenol is a much more robust material that many smart materials and can withstand tensile and bending loads. Also, the recent ability to manufacture Galfenol at the nano-scale will allow design of high resolution sensors. These characteristics make Galfenol a promising choice for use in novel sensor systems.

The study described in this paper focuses on a prototype sensor grid array at the macro scale (1/8" diameter Galfenol rods) with the intent of investigating the grid and circuit designs for optimization and future scaling to the nano-level. A grid array of Galfenol (Fe82Ga18) was designed as part of a magnetic circuit. The circuit contains a permanent magnet that produces a certain initial level of flux. Beneath the rods, flux concentrator paths carry the flux to Giant MagnetoResistive (GMR) sensors. When force is applied to a section of the sensor, the Galfenol rods in this area undergo a change in permeability which changes the flux flowing through them and into the GMR sensors. The sensors measure the level of force applied according to the amount of flux change detected. Also, the grid arrangement of flux concentrators and sensors enables the determination of the force location. The known force levels and locations are then combined to produce a visual map. Such information proves useful in surface texture detection and when working in areas where visual feedback from cameras is not available.

Future advancing designs of this sensor array will utilize nano-sized Galfenol rods. Therefore, this study investigated a few particular aspects of the circuit and grid array design in order to optimize the system and find correlations for application to the future nano-scale work. The distance between the flux concentrator paths required compared to the rod size was optimized for minimal flux leakage and flux crossover. Also the level of initial flux provided by the permanent magnet vs. the change in flux for certain changes in force applied was tested to find the ideal level for GMR sensor detection.

A tactile sensor that can provide high resolution force feedback in a small, lightweight package will provide great capability in many engineering fields. This study proves the feasibility of the Galfenol sensor system and provides critical data for scaling the system to the nano-level in the future.

6173-37, Session 8

Tactile display array based on magnetorheological fluid

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A tactile display is a programmable device whose controlled surface is intended to be investigated by human touch, as a finger is dragged over it. It has a great number of potential applications in the field of virtual reality and elsewhere.

A typical tactile display is an array of independently controllable actuator elements that are able to exert (or resist) forces in the direction normal to the user's skin surface. By proper control of these actuators, an impression, similar to that when an actual object is touched by human's finger, can be generated artificially. Researchers have proposed a wide variety of pin or vibrator arrays to present the sensation of 3 dimensional local shapes, fine textures, and slippage of grasped objects. These tactile displays use many actuating techniques, ranging from Electrorheological fluid, shape memory alloy, piezoelectric ceramic, ionic conductive polymer gel film or a simple mechanical approach using miniature electric motors.

The previous research work on ER fluid based tactile displays highlights the possibility of constructing a tactile display in a very simple way - there are no moving components and few accessories for its operation. Though the ER fluid tactile display has excellent performance, there are still some disadvantages to limit its application such as high driving voltage, lower yield stress and the requirement for the fluid and components to be strictly free from impurities. To overcome these problems, using MR fluid as an alternative actuating method was proposed.

Magnetorheological (MR) fluids are suspensions of micron sized ferromagnetic particles dispersed in varying proportions of a variety of non-ferromagnetic fluids. MR fluids exhibit rapid, reversible and significant changes in their rheological (mechanical) properties while subjected to an external magnetic field. MR fluids are becoming increasingly important in applications concerning active control of vibrations or switching/control of torque/force. Devices such as dampers, shock absorbers, isolators, clutches and brakes have all been designed.

In this research, a prototype tactile display incorporating magnetorheological (MR) fluid has been constructed and investigated. Surface force responses of the tactile display under various magnetic fields have been measured while a probe was moved across the upper (controlled) surface. As the applied magnetic field was varied, the sensed surface profiles changed in synchronisation with the magnet field strength. This preliminary research provides a new practical and effective way of achieving a tactile display without any moving components.

6173-38, Session 9

Development and verification of real-time controllers for the F/A-18 vertical fin buffet alleviation

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Buffeting is an aeroelastic phenomenon that plagues high performance aircraft, especially with those with twin vertical tails such as the F/A-18. At high angles of attack, unsteady vortices that emanate from the wing leading edge interact with the vertical tail structure. This broadband buffet load excites the bending and torsion modes of the vertical tail, resulting in significant dynamic stresses in the tail structures, which not only reduce the fatigue life of the structure, but also decrease mission availability. A smart structure based solution for this problem on the F/A-18 empennage was pursued as an international technical collaboration activity among Australia, Canada and the United States under the auspices of The Technical Cooperative Program (TTCP). The approach was an advanced hybrid actuation system that controlled the two primary modes, first bending and first torsion, separately. The conventional electro-hydraulic rudder actuator was used to provide inertial loading from the rudder to control the first bending mode. The first torsion mode was controlled using surface mounted Macro Fiber Composite (MFC) conformable actuators located on the upper third portion of the fin. This paper describes the development of real-time control laws, based on the Linear Quadratic Gaussian (LQG) algorithm, through extensive numerical simulations. Furthermore, the performance of these control laws was verified through the full-scale closed-loop ground vibration tests conducted in the IFOSTP test rig in Melbourne, Australia, in September 2004.

The LQG algorithm was chosen to develop real-time controllers because of its advantage in balancing the controller performance with the control effort and its ability to account for process and measurement signal noise. It is necessary to obtain a representative dynamic model of the structure in order to develop an effective control law based on the LQG algorithm. The complexity of the hybrid system and the non-linearity of the full-scale tail structure enhanced the difficulty in modeling. Therefore, an experimental system identification approach was used to obtain state space models of the baseline structures as well as the rudder and the MFC systems. Based on the state space models, Multi-Input-Multi-Output (MIMO) real-time control laws were developed to regulate the rudder and the MFC systems to reduce the strain at critical locations of the fin under representative buffet excitations. The performance of the controllers was evaluated through extensive numerical simulation using Matlab/Simulink. The simulations showed that the bending mode and torsion mode were suppressed by 36% and 60%, respectively, for 50% maximum damage buffet excitation condition as measured by an accelerometer located at the aft tail tip. Once the control law was validated through simulations, it was implemented using the Matlab xPC Target hardware platform to perform closed-loop ground vibration tests on the full-scale F/A-18 vertical fin. The experimental results verified the validity and the effectiveness of LQG real-time control laws to suppress both the first bending and the first torsion modes of the vertical tail. The vibration suppression performance from the closed-loop test correlated well with simulation estimates. The full-scale tests on the F/A-18 empennage demonstrated that the advanced hybrid actuation system was a feasible solution to alleviate vertical tail buffeting damage in high performance fighter aircraft.

6173-39, Session 9

Efficiency improvement of a new vertical axis wind turbine by individual active control of blade motion

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Recently the demand for the alternative energy has increased because of environmental problems such as carbon dioxide and the drain on the energy resources. A wind power is one of the most important parts of the alternative energy, and it is growing rapidly. A wind turbine system is classified into two groups according to the direction of rotating axis to the ground; a vertical axis wind turbine and a horizontal axis wind turbine. A vertical axis wind turbine is known to be easy construction, operation and maintenance since all the equipments can be installed in the ground. The Darrieus wind turbine developed in the 1920s is a representative one of a vertical axis type. But it is not popular as a wind turbine system because it is inefficient for power generation and the blade shape erodes the easy operation and maintenance. Thus other type of a vertical axis wind turbine such as the straight blade type is appeared. And small one is commercialized in some countries including Japan. But all these vertical axis wind turbines have limited power generation due to their fixed pitch angles.

In this paper, a research for the performance improvement of the straight blade vertical axis wind turbine is described. For the system consists of several blades rotating about axis in parallel direction, the pitch angle variation of each blade and the airfoil shape are aerodynamically optimized.

This research is focused on the development of a small vertical axis wind turbine in the 2kW class. Rotor system has four blades consists of 2m span and 0.45m chord and its radius is 1.6m. Airfoil shape is determined by shape optimization methodology that geometry and angle of attack are design variables and power generation is an object function. A general purpose commercial CFD program, STAR-CD is used for numerical analysis and cluster computer in our laboratory that is 1.3 TFlops class is used for parallel computing. And PCL of MSC/PATRAN is used for efficient parametric auto mesh generation. From this analysis, power generated is obtained according to the combination of each variable. And optimum pitch angle of the system is produced by the change of the wind direction, the wind velocity and the rotating speed.

Based on data obtained from above analysis, control device that is the most important part of developing system for pitch angle and phase angle variation is realized. For this purpose, the wind direction and the wind velocity are sensed and each blade is actuated to optimal values by servo motor.

6173-40, Session 9

Development of a morphing structure with the incorporation of central pattern generators

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Organic life forms have adapted to their environment since dawn of time. In this vast time span, plants and animals alike have grown to live in synch with their surroundings. The anatomy of individual cells to tissues to organs has permitted the perpetuation of life and has beneficial characteristics. A current goal in mechanical engineering is to understand the efficient anatomies of both structures and controls. These biological mechanisms can then be adapted and improved upon. In this project, an active truss structure will be designed and tested to examine its load bearing and morphing capabilities. Actuators will replace passive members in this structure to achieve shape change. The controls will integrate artificial central pattern generators (CPG) to mimic the natural counterpart of the nervous system. Project goals include modeling, constructing, and deflection analysis of the morphing system. An analytical solution to describe the deflection of the structure will be derived and compared with experimental results to illustrate the static capabilities of the structure. Analytical and experimental verification of the CPG will demonstrate the dynamic properties of the morphing structure. The seamless integration of the structural design, material selection, and control methods will indicate success.

6173-41, Session 9

The optimization of a tensegrity wing for biomimetic applications

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Tensegrities are excellent candidates for structures used in biomimetic applications. By integrating active cables into these structures they offer a light-weight system with large morphing capabilities. They mimic a musculoskeletal system without the constraint of a stiff skin allowing for double curvature and the mimicking of full three dimensional shapes that are often present in the motions of animals. This paper investigates beam and plate tensegrity structures under the influence of external loads where cables are activated to change the overall shape similar to the biological equivalent of a musculoskeletal system. Since the actuation model is built on the contributions of individual actuators and not a collective group of actuators a practical solution to shape changing can be found. Furthermore the biological shapes are correlated with the structure's shape through an optimization routine that reveals the minimum number of actuators and their locations to reach the measured biological displacement field.

6173-42, Session 9

Mechanical design of biomimetic fish robot using LIPCA as artificial muscle

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Recently, many researchers realized that biological creatures exemplify sophisticated yet simple movements in terms of their maneuverability and speed. Therefore, there has been a vast amount of efforts dedicated to mimic nature's technologies in order to build bio-inspired mechanisms. In term of actuation, for particular purpose, there is a shift from motor to smart materials. LIPCA (Lightweight

Piezo-composite Curve Actuator), a kind of smart material with good actuation displacement and force, was used as actuator for flapping wing device and its experimental results showed that the flapping device actuated by LIPCA could generate lift and thrust.

It is our purpose to design, build, and develop a LIPCA-actuated biomimetic fish robot which is capable of producing thrust. There are many fish swimming modes, but most fishes swim by undulating their caudal (tail) fins. Our biomimetic fish robot tries to mimic this undulatory movement. Here, LIPCA is used as artificial muscle which actuates caudal fin of biomimetic fish robot, thus producing undulatory (tail beat) movement. If the undulatory movement exists, there is a possibility that thrust can be generated.

So far, we have tried to build two models as a demonstrative proof of concept. The model, limited to posterior part, consists of posterior body and caudal fin. The first model uses one LIPCA with simple beam arrangement mounted on robotic platform. The actuation point is on the center of LIPCA. LIPCA is then connected to linkage system which is capable of converting LIPCA's actuation into caudal fin movement. The second model uses two LIPCAs placed parallel to each other with different curvature orientation such that those LIPCAs simultaneously produce more force. One side of LIPCA is fixed to robotic platform and the other side is fixed to revolute joint. This revolute joint is connected to small strip. Also, this strip is connected to the other revolute joint which also is connected to the other LIPCA.

The robotic platform is mainly made from balsa wood, while caudal fin is made of stiff and flexible materials. The fin material combination is designed to produce vortices which eventually increase thrust. The body part is insulated to prevent short current. Testing was done in water tank using 400 Vpp input voltage and 2 - 16 Hz frequency. From the preliminary experiment, the model showed the existence of tail beats. The experimental results also indicate that the swimming speed of biomimetic fish robot can be controlled by adjusting the frequency of input voltage.

6173-43, Session 10

Development of smart material systems based on composites

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Structural materials should become more sensitive and active, being adaptive to their environment and being able to cope situationally in order to increase efficiency and reliability, decrease cost, and eliminate accidents. In this paper, several new concepts the author has proposed and demonstrated to realize this kind of systems, that is, metal and/or polymer based sensitive and/or active structural material systems suitable for health monitoring and/or actuation and/or self-repair are introduced. Most of the developments have been done by simple and innovative methods and by using conventional and low cost materials without using sophisticated and expensive sensors and/or actuators. The following topics were mainly examined. (1) Embedment of commercially available optical fiber in aluminum and SiC fiber reinforced aluminum composite to use as a sensor for health monitoring, and so on. Optical fiber was successfully embedded in aluminum matrix by the interphase forming/bonding (IF/B) method invented by the author, and fracture process and wear of continuous SiC fiber/aluminum composite could be monitored with the embedded optical fiber. (2) Formation of optical interference and loss type strain sensors in epoxy matrix and CFRP simply by embedding prenotched optical fiber and fracture of it in them. This type of sensor is simple, compact, robust and low cost. In the case of single notched optical fiber, an optical interference type sensor to detect small and precise strain was easily formed. In the case of multiply notched one, an optical loss type sensor for measurement of large strain was easily obtained. (3) Fabrication of a multifunctional sensor for aluminum and its composite to monitor their temperature, strain, fracture process, and so on. It was successfully made by embedding an oxidized nickel fiber (NiO/Ni composite fiber) in them. A part of the oxide was removed before embedment to make a metallic contact between the nickel fiber and aluminum matrix to generate thermal electromotive force for temperature measurement. Strain was reflected on electrical resistance change of the embedded fiber. This type of sensor is also very simple and low cost. (4) Development of active and sensitive composites for active shape control, and so on, using conventional structural materials. An active laminate of CFRP (works as "bone" and "blood vessel")/epoxy (as insulator)/aluminum (as "muscle")/electrode (to apply voltage on CFRP), of which unidirectional actuation was realized by electrical resistance heating of carbon fiber in the CFRP layer and its curvature change could be monitored using optical fiber multiply fractured in the CFRP layer (works as "nerve"). (5) Fabrication of active fiber-reinforced metals such as SiC/Al and SiC/Ni systems by laminating a reinforced layer with a unreinforced layer to cause thermal deformation. In the case of SiC/Al composite, actuation was performed only in the fiber direction and is useful for making a light weight active panel. In the case of SiC/Ni composite, actuation took place up to beyond 1200K and is useful for making a high temperature active material.

6173-44, Session 10

Active rigidization of carbon-fiber reinforced polymer composites for ultra-lightweight space structures

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An active approach for initiating rigidization in carbon-fiber reinforced polymer (CFRP) thermosets unites electrical resistivity to mechanical stiffening. In efforts to develop an active method for composite rigidization of ultra-lightweight and gossamer space structures, temperature-controlled resistive heating is used to create on-command rigidizable materials. As required by the on-orbit conditions in space, flexible, rigidizable structures demand stable and space-survivable materials that incorporate techniques for providing shape control and structural stiffening. Methods currently employed to achieve a mechanical hardening include mostly passive techniques: UV curing, sub-Tg curing, solar heating, hydro-gel evaporation. The benefits of a passive system (simplicity, energy efficient) are offset by their inherent lack of control, which can lead to long curing times and weak spots due to uneven curing. With the ability to significantly reduce the curing time of the composite from a structurally vulnerable state to a fully rigidized shape and to increase control of the curing process, an active approach is taken. Specifically, PID feedback control during internal resistive (Joule) heating establishes an electrically-controlled, thermally-activated material. This research examines how selective temperature control is applied to the resistive heating of CFRP materials. Parametric studies of how various control parameters (including curing temperature and time) affect the increased stiffness of the material are performed. Previous work verifies resistive heating as a viable solution for initiating mechanical stiffening in CFRP materials. Even without feedback control, open-loop resistive heating on a similar CFRP composite (one without a curing agent) achieved 2-3 times the stiffness of the original tow. In doing so, it successfully demonstrated how a polymer matrix is used to strengthen a CFRP composite in the direction of the fibers. Feedback control, using a PID control algorithm, was then applied to the process of resistive heating. Precise temperature tracking (less than 1°C error at steady state) was achieved for controlled sample heating. Using small samples of the polymer-coated, carbon-fiber tow, composite hardening through resistive heating occurred in only a few minutes and required less than 0.1 W-hr/inch of electrical energy. With a controlled curing technique, the effect that both the curing temperature and time has on rigidization will be examined. Particularly, the increased stiffness will be related to these control parameters in order to better tune the curing process.

6173-45, Session 10

Modeling of low-frequency coupling effect in magnetostrictive-piezoelectric layered composites

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A theoretical model is developed for the low-frequency (i.e. less than 10 Hz) magnetoelectric (M-E) coupling effect in magnetostrictive-piezoelectric layered composites (MPLC). The M-E voltage coefficients alpha, defined as the ratio of the induced electric field (in the piezoelectric material) to the applied ac magnetic field , are derived to determine the performance of M-E effect in the MPLC. Different modeling configurations; including longitudinal mode, transverse mode, and in-plane mode, are presented and studied with respect to the volume fraction of piezoelectric material and the effective stiffness of magnetostrictive layer. The results show that the peak values of M-E voltage coefficient change with these parameters which can be affected by different materials and fabrication methods. However, the highest value always occurs in in-plane mode configuration. An effective coupling factor, magnetoelectric coupling coefficient, k, is also introduced to determine the efficiency of energy conversion or storage in the MPLC. Electro-elastic (EE), magneto-elastic (ME), and electro-magnetic (EM) coupling coefficients are discussed under different configurations in this paper.

6173-46, Session 10

Magnetoelectric response of piezoelectric/ magnetostrictive/ piezoelectric laminate composite

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The theoretical analysis of magnetoelectric performances in long-type piezoelectric/magnetostrictive/piezoelectric (PMP) laminate composite is presented in this paper. The laminate composite is supposed to be used as magnetoelectric transducer free of coils. The piezoelectric laminates are designated to be poled in their longitudinal direction. The equivalent circuit of the composite is developed based on the constitutive equations of magnetostrictive and piezoelectric effects and the motion equation. This way the coupling between piezoelectric and magnetostrictive layers is characterized by the connection of the equivalent circuit components. In term of the equivalent circuit, it is straightforward to obtain the magnetoelectric response of the laminate composite. According to the equivalent circuit, the electric response, which is defined as the voltage of either piezoelectric laminate, is derived under the applied static and harmonic magnetic field in both longitudinal and traversal directions. Based on this, the parameters of the implementation of the composite, such as the thicknesses of laminates, the poled mode of piezoelectric and magnetostrictive (Terfenol-D) laminates and the direction of the applied magnetic field, is analyzed to obtain an optimal magnetoelectric response. Compared with the magnetostrictive/piezoelectric/magnetostrictive (MPM) laminate composite, the value of voltage output in one piezoelectric laminate is almost half of that in the MPM laminate composite. By connecting the two piezoelectric laminates electrically in cascade, the voltage output may almost be the same as that in MPM laminate composite. However, the electric output power in PMP laminate composite is half that in MPM laminate composite. In the paper, the frequency response of the PMP laminate composite is also discussed. Experimental results are included to show the validness of the theoretical analysis.

6173-47, Session 10

Study of a reinforced concrete beam strengthened using a combination of shape memory alloy wires and carbon fiber reinforced polymer plates

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Traditional methods used for strengthening of reinforced concrete (RC) structures suffer from inherent disadvantages ranging from difficult application procedures to lack of durability, such as bonding of steel plates. In recent years, strengthening of RC structures using carbon fiber reinforced polymer (CFRP) sheets or plates has attracted considerable attentions around the world. Carbon fiber reinforced polymer (CFRP) sheets or plates can be used to strengthen a reinforced concrete (RC) structure well. Most existing research on CFRP plate bonding for flexural strengthening of RC beams has been carried out for their strength enhancement. However, little research is focused on effect of residual deformations of existing structures on the strengthening. Existing residual deformations of the RC structure in service play a negative role in this strengthening. The existing structures surely have the residual deformations or strains when subjected to various loads prior to CFRP plate bonding. In addition, the residual deformations have an important effect on the following strengthening. But there exists a very significant challenge how the residual deformations are reduced. Shape memory alloy (SMA) has showed outstanding functional properties as an actuator, such as large recovery stress (maximum recovery stress is 700MPa or so), high recovery strain (about 8%), distinguished fatigue property, variable elastic modulus with phase transition state and so on. Therefore, Shape memory alloy (SMA) is well-known as an excellent actuator which can generate considerable recovery forces during its reverse martensitic transformation. It is a possibility that SMA can be used to make cracks of concrete close and repair some concrete structures by imposing the recovery forces on the concrete. The repair by heating SMA wires embedded in concrete infrastructures is very essential because large-scale and important structures need to be offered enough waiting time for permanent repair when encountering dangerous situation, such as cracking in some very important RC structures. However, it is only an emergency damage repair for civil structures since the SMA wires need to be heated continuously. Therefore, an innovative method of a simple RC beam strengthened by CFRP plates in combination with SMA wires was first investigated experimentally in this paper. Test results indicate that recovery forces of the SMA wires can decrease midspan deflections of the specimens and even make cracks of the concrete close. More embedded SMA wires lead to reducing of more residual deformations. The steel main bars have a negative role in decreasing the deformations. The small residual deformation obtained by driving of the SMA wires results in a relatively large stiffness of the specimen strengthened later using the CFRP plates. In addition, the famous nonlinear finite element software of ABAQUS was employed to analyze and simulate the RC beams strengthened by CFRP plates in combination with SMA wires. It can been found that it is an excellent strengthening method that a permanent repair of the RC beams using the CFRP plates is conducted following an emergency damage repair using SMA wires.

6173-48, Session 11

Verification of robustness in smart composite structures

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In order to implement health monitoring methods in composite material structures that are being developed and manufactured a series of preliminary tests was conducted.

The aim was to check the influence of the sensors on the structure, their durability and their ability to detect changes in the structure.

As a first step a contact was made with Acellent Technology Inc. who developed and produces the measurement system and sensors: SMART Suitcase(tm) and SMART Layer(r).

A planar specimen (plate) was manufactured, with an implant of SMART Layer(r). The plate was composed of graphite/epoxy composite material.

The pre-preg was woven in a direction, the plates consists 9 layers of pre-preg, while the SMART Layer(r) was positioned between the third and fourth layers.

In addition a mounting device for the graphite-epoxy plate was manufactured, in order to create different boundary conditions on the plate edges.

We conducted a series of preliminary tests in order to check the mechanical and electrical properties of the plate-sensor system (strength, rigidity, PZT capacitance, response to voltage input).

Subsequently, we performed experiments made to detect damage and changes in boundary conditions imposed on the plate. Damage was simulated by placing play dough on the surface of the plate, and its position was estimated. Changes in the boundary conditions were applied by systematically unfastening the bolts of the mounting device and identifying which ones were unlocked.

Loading experiment

In this test we checked the influence of loading of the composite plate on the PZT sensors implemented in the plate. We checked the durability of the sensors and of the plate. In addition, we measured displacement vs. load to verify calculated models (analytical and FE). These measurements were compared with measurements of unimplanted plates to examine the influence of the SMART Layer(r).

In the next step the plates were loaded until failure occurred and the survival of the PZT sensors was checked by measuring their capacitance. The outcome of the experiments showed that the SMART Layer(r) increased the graphite-epoxy plate's flexibility. The sensors were found to survive this procedure with no distinguishable damage.

We have also perceived a rise in capacitance as a function of the load and the distance of the sensor from the edge of the plate (probably an indication of strain).

Application to voltage input

The target of this test was to characterize the reaction of the plate-sensor system to a voltage input. Having these characteristics we could predict reaction of the plate to a known input.

A sine scan in the range of 0-4000Hz was made, in order to find the first modes of the plate and compare them to calculated modes.

We have found, by scanning, changes in the modes between fully restrained plate and free edges plate. This can show probability of using the method of modal analysis in analyzing the plate condition.

A second test was made to find appliance of the plate to different voltage input. In this case we have also found major different reaction while applying different boundary condition.

Time domain experiments

We have conducted tests using the ACESS(tm) software, purchased from its developer Acellent technologies inc.. The software produces transient signals (Burst, Chirp, Random) and plots the reaction of the sensor while allowing calibrations of the signal parameters and signals sampling.

Our tests were made to find changes in boundary condition by loosing tightened bolt in the plate perimeter and also loading the plate in deferent locations.

The input signal was Burst3 in 60-100Khz. We received visual verification of loosed bolts.

The last test made to check if we could locate damage in the plat. The damage was presented as a play dough attached to the surface of the plate. By using this method (recommended to us by Acellent) we could conduct large amount of tests on the same plate.

In order to demonstrate the abilities of the method, signal processing was applied on the signals and allowed us to spot the damage.

6173-49, Session 11

Design, fabrication, and testing of a SMA hybrid composite jet engine Chevron

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Reduction of jet engine noise in the vicinity of airports continues to be of paramount importance. Recent research has shown that chevrons applied to the exhaust nozzle can reduce jet noise by as much as 2-3 dB (EPN). Chevrons produce a “scalloped” trailing edge to the nozzle and they protrude into the flow, increasingly from root to tip, in the flow-wise direction. The noise reduction studies to date have been performed using “static” chevron technology, where the geometry and resulting flow immersion is predetermined and invariant. It has also been shown that the presence of the static chevrons induces a thrust loss of approximately 0.25%. Thus, there exists a tradeoff between noise reduction at takeoff/landing and thrust reduction at cruise.

Several research groups have proposed development of deployable chevrons to minimize this thrust penalty. Most known deployable concepts involve the use of shape memory alloys in some form. This paper will present results from a research effort to design, fabricate, and test a novel and unique adaptive chevron concept based upon SMA actuators embedded in a composite structure, termed a SMA hybrid composite (SMAHC). The concept lends itself to power-efficient electrical and/or autonomous environmental activation for versatility in design studies as well as in-flight optimization. Previous work demonstrated the feasibility of the approach, but performance objectives were not achieved.

Recent work has refined the fabrication approach significantly to produce repeatable and reliable SMAHC chevrons in a flat configuration that meet the performance objectives. A recently commercialized numerical model for SMAHC structures was used to develop the chevron design and numerical results have been correlated successfully with bench top experimental results. Hardware has also been designed and fabricated to integrate the SMAHC chevron into a nozzle configuration for wind tunnel testing. A single flat SMAHC chevron has been configured on a square nozzle and tested in the NASA LaRC Small Anechoic Jet Facility (SAJF) for evaluation of the chevron performance under representative flow conditions. Performance objectives were also met with flow and deformation-based closed loop control was demonstrated. Details of the new fabrication processes, bench top and SAJF experimental setups, computational models, and results from bench top and SAJF experiments will be presented.

6173-50, Session 11

Design and testing of integrated Bragg grating sensor systems for advanced grid structure

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Lightweight and highly reliable composite structure is a key element of a next generation aircraft system. A grid structure, consisting of multiple ribs (unidirectional CFRP laminate) in a truss-like arrangement, has structural simplicity, and is hence attractive for the aircraft system. The authors are attempting to construct a health monitoring system on the grid structure using fiber Bragg grating (FBG) sensors in order to enhance the structural reliability and the maintenance efficiency. Among many non-destructive evaluation methods for composite structures, FBG sensors are especially attractive due to the high sensitivity, the lightweight, and the small size. Moreover, FBG sensors can be so easily embedded and integrated into the grid structure during its manufacturing process that there is less difficulty in developing a large-scale sensor network.

Prototype of the grid structure (525mm x 550mm) was fabricated with high modulus type CFRP, and 29 FBG strain sensors were embedded in this grid structure. Each ribs had one embedded FBG sensor. Strain distribution from all FBG sensors was monitored during a bending test. Considering the applicability of this health monitoring system, sampling rate was set as faster as possible using a combination of a polychromator-based FBG monitor and a MEMS-based optical switch. Furthermore, damage detection was attempted by comparing the measured results with the strain database of the “non-damaged” grid structure.

6173-51, Session 11

Experimental evaluation of instantaneous phase-based index for structural health monitoring

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Structural health monitoring (SHM) aims at developing a damage identification method that provides complete damage information (location, type, and severity), without false indication, for changing environmental and operational conditions and noisy data (i.e., ‘real world’ situations). Numerous approaches for extracting damage sensitive features based on vibration measurements have been investigated by various researchers. A novel signal processing method based on empirical mode decomposition (EMD) and the Hilbert transform has been proposed, which is known as the Hilbert-Huang transform (HHT). The EMD produces instantaneous magnitude, frequency, and phase information for any general signal and may be used for analyzing non-stationary and nonlinear processes (in addition to linear and stationary signals), which makes this approach particularly suitable for identifying structural damages under ambient loading. Our previous work used the HHT method for experimental damage identification in a continuously monitored multi-level structure. Both the presence and location of damages were determined successfully when the damages occurred suddenly (such that the damaging event had a high frequency response) and the sensor noise was low.

Some researchers have recently suggested exploiting instantaneous phase features of the signal (generated through the EMD process) combined with wave mechanics based concepts for damage detection. The instantaneous phase represents the phase of a traveling structural wave of a dynamically measurable quantity, such as acceleration. The basic idea is that any damage in a structure will alter the speed at which energy traverses the structure. Therefore, the difference in phase functions between any two points on the structure is altered if the structure is damaged. A damage index based on phase functions has shown promise in the limited experimental results reported so far. We plan to investigate the instantaneous phase based index for structural health monitoring of civil infrastructure. The first phase of this research (to be reported in the final paper) focuses on laboratory tests. The test article comprises a 71" long beam with eight wireless sensor nodes. This test beam features the ability to initiate controlled and repeatable damage scenarios using PZT based mechanism in order to simulate various locations and levels of damage. At Clarkson University, we have been developing a Wireless Intelligent Sensor and Actuator Network (WISAN) capable of precise, real-time and time-synchronized data acquisition on massive arrays of heterogeneous sensors. The WISAN architecture is a two-level cluster-tree architecture, providing fault tolerance not present in other sensor networks proposed for SHM. We plan to integrate the WISAN with the proposed research in instantaneous phase based damage index to realize a complete structural health monitoring system.

6173-52, Session 11

Application of a vibration-based damage detection algorithm on a structural health monitoring benchmark problem

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In recent years there has been great interest in the development of a structural health monitoring (SHM) methodology using vibration measurements. The value of such a methodology, allowing for early detection of damage in a structure, is obviously immense considering the large amount of aging infrastructures worldwide. The idea of using dynamic data for damage detection is especially attractive because it allows for a global evaluation of the condition of the structure in contrast to local techniques which search for damage in a local region at a given time, which makes them expensive and time-consuming to apply for global structural condition assessment. SHM using vibration monitoring is based on the idea of establishing differences in the modal properties of a structure using dynamic response data before and after damage. Based on changes in Power Spectral Den-

sity (PSD), this paper proposes a damage identification technique that detects damage and its location. The paper addresses the benchmark problem on structural health monitoring. This problem was recently developed by the ASCE Task Group on Structural Health Monitoring. The benchmark study was created to facilitate the comparison of several methods employed for the health monitoring of structures. The structure selected for the benchmark problem is the four-story 2-bay by 2-bay steel braced frame. The damage was introduced by removing brace elements or disconnecting the beam-column bolted connections. The present paper focuses on different cases of this benchmark problem assuming unknown input. The proposed method is shown to be very effective for damage identification, and is relatively insensitive to noise in the sensors. Different issues regarding the performance, limitations and difficulties of this methodology are discussed.

6173-53, Session 11

Structural health monitoring of CFRP pressure vessel by using fibre optic AE sensors

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In recent years, advanced composite structures are used extensively in many industrial areas such as aerospace, aircraft, automobile, pipeline and civil engineering. The reliability and safety is the key of the advanced composite structure that is often used under harsh environment. The structural health monitoring (SHM) in-service is very important and definitely demanded for safely working of high performance composite structures in-situ. A sort of non-destructive evaluation (NDE) techniques have been developed in the past including ultrasonic scanning, acoustic emission (AE), shearography, stimulated infrared thermography (SIT), vibration testing, etc.. The challenge is to develop new techniques which can perform the on-line structural heath assessment started from manufacture of composite structures to the real service of these structures in field. It is very difficult to carry out by using conventional methods.

A unique opportunity was provided to real-time monitor the health status of composite structures by using smart materials and structures. Smart materials and structures, not only have traditional structural materials' functions, but also have actuating, sensing and microprocessing capability. Fibre optic sensors (FOSs) are very important sensors used in smart materials and structures because of their many advantages. One of the main advantages is that these sensors are very light in weight and small enough that they can be embedded in composite materials in a nonobtrusive manner that does not degrade structural integrity. Fibre optic sensors in smart structures are an enabling technology that will allow engineer to add nervous system to their designs, enabling damage assessment and many other capabilities to structures that would be very difficult to achieve by other means. In response to the increased need of smart structure, various techniques are being developed and some of the most promising are based on the use of fibre optic sensors (FOS).

In this paper, two kinds of fibre optic acoustic emission (AE) sensors including Fibre Bragg Grating (FBG) sensor and intensity fibre optic sensor based on single mode fibre tapered fused coupler have been developed and investigated. By the way, the non-destructive evaluations (NDE) of CFRP pressure vessels embedded fibre optic acoustic emission (AE) sensors have been performed under burst test. The two kinds of fibre optic AE sensors have also been used to monitor the damage growth of CFRP pressure vessels. The experimental results obtained indicate that the fibre optic AE sensors performs adequately in CFRP environment and there is very good correlation between results obtained by the fibre optic sensors and conventional piezoceramics AE sensors. The burst failure pressure of composite pressure vessel could be precisely predicted using AE parameters of fibre optic sensors under lower test pressure. There will be also great benefit to monitor the structural health status of composite vessels if we could locate the damage areas using fibre optic AE sensors array.

6173-54, Session 12

Development of constitutive relations for a dual collocated FBG sensor written into a polarization maintaining panda fiber embedded between two different matrix materials

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Fiber Bragg Gratings (FBG) written onto birefringent Polarization Maintaining (PM) fibers have been known to exhibit characteristics that make them ideal for simultaneous strain and temperature measurement when embedded in a matrix. In this research, the potential benefits of using FBG sensors in localized strain and temperature monitoring of hybrid composite structures is examined. To address this, new constitutive relations are being developed for dual collocated FBG sensors written along the polarization axes of a PM panda fiber embedded between two different matrix materials. The resulting model will enable determination of the stress fields within the fiber and the surrounding matrix for a single lamina. This approach is an extension of Goldberg's [1] work in the area of unit cell based slicing micromechanics analysis for polymer matrix composites. The procedure is computationally efficient, since due to symmetry considerations, only one half of the unit cell (known as analysis cells) need to be analyzed for both matrices under investigation.

Prior experiments using the panda fiber as a sensor have ignored shear stresses and stresses transverse to the fiber direction. However, such effects may be significant in applications such as composite pressure vessels, electronic packaging assembly, hybrid composite structures, and wear detection in naval marine propulsion systems to name a few. For such applications fiber optic sensors offer a viable nondestructive method to monitor changes in strain fields. In order to account for these shear stresses, the current model will include measurement of transverse shear stresses in the Panda fiber.

The developed model will result in expressions for effective stresses in terms of effective strains for each slice within the analysis cell, which will then be used to determine overall effective stresses as a function of effective strains and temperature changes for the entire unit cell using laminate theory. The stresses in the core region of the fiber will be computed using strains and temperature changes as predicted by FBG sensor theory in a PM fiber. These strains and temperature changes will be determined by monitoring changes in reflected Bragg wavelengths. The Bragg wavelengths of the two collocated FBG sensors will be far apart so as to make them distinctly discernible on the reflection spectrum. Light from a broadband source will be directed into a typical 1.55 μm band panda fiber. In the absence of external perturbations, the sensor with the higher Bragg wavelength is expected to show a peak to peak separation of about 0.5 nm for the fast and slow polarization modes. An increase in temperature is expected to reduce the peak to peak separation between the fast and slow modes while an increase in strain is expected to lead to a uniform shift in peaks for both modes.

1.Goldberg, R.K.; "Implementation of Fiber Sub structuring into Strain Rate Dependent Micromechanics Analysis of Polymer Matrix Composites" 2001.

6173-55, Session 12

Energy transfer across cracks in a thin membrane strip

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As interest in deployable, large, ultra-lightweight structures continues to grow, more and more membrane structures will be deployed for prolonged use. It is important therefore to have systems in place that enable health monitoring and diagnosis of membrane structures during operation. Integrated health monitoring systems (IVHS) are commonly used (Lane, 2004) on aircraft wings, helicopter rotors, etc. (Tumer, 2003). Recently reported research also includes health monitoring of lightweight composite panels (Yuan, 2003). However, published literature on health monitoring of ultra-lightweight membrane structures seems be limited. In this paper, we present recent theoretical and experimental results on the detection of cracks in a membrane using a non-collocated transducer-receiver pair. In particular, current focus is on investigating the effect of thin cracks that lie between the transducer and the receiver, which are located at different ends of the structure.

The work described in this paper aims to simulate a situation where a number of piezoelectric transducers and receivers are distributed over a membrane. Intermittent voltage pulses applied at the transducers generate propagating acoustic waves through the membrane. These waves are sensed by the receivers, and the presence and location of a crack could then be detected by processing the recorded signals at the various receivers. It is important therefore to know the multiple-input - multiple-output transfer function relating the received signals to the input signals, and to have available models quantifying the effect of crack location and size on this transfer function. For thin membranes, the crack dimensions need not be too large to alter this transfer function in a significant but complex manner. Therefore, detailed studies are required to develop a good understanding of the effect of cracks on the wave propagation transfer functions for membranes, and to investigate how the time-domain pulse response of a cracked membrane may be interpreted to estimate the size and location of a crack.

In this paper, a fixed-fixed Kapton membrane strip is excited at one end by a polyvinilidene fluoride (PVDF) transducer. A receiver of identical specifications is located at the other end. By applying sinusoidal input voltages to the transducer over a wide frequency range and sensing the voltages produced at the receiver, the transfer function amplitude could be computed. Fourier transform based (FFT) filtering was used to eliminate the effect of noise frequencies. Next, an arbitrary wave form generator was used to apply a single-sinusoid pulse at the input, and the response at the output was recorded. Cracks were introduced next near the center-span, and both the transfer function and the pulse response functions were re-determined for analysis and for use in the crack size/location estimation procedure. Results indicate that the transfer function is not flat, leading to an interesting pulse response at the receiver, which is altered considerably in amplitude with the introduction of a crack.

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6173-56, Session 12

Structural damage detection based on videogrammetric and wavelet technique

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The availability of inexpensive and high-resolution commercial digital video cameras has brought forth a new area of application that based on the processing of high quality of digital images. Videogrammetry is a three-dimensional measurement technique that combines the traditional photogrammetry and the computer vision technique. This technique has been previously demonstrated to provide reliable accuracy comparable to that of the traditional sensors for dynamic measurement. Potentially, the technique can measure three-dimensional deformation time history of either a few selected targets or a continuous spatial profile on a structure. In this paper, a technique based on videogrammetry and spatial-temporal wavelet transform is proposed for structural damage detection. A videogrammetric technique that can measure deformation with sub-pixel accuracy is first established to extract the temporal-spatial deformation of a structure. Spatial-temporal wavelet transform is then applied to detect structural abnormality in the image sequence. The proposed technique is illustrated on two structures in the laboratory: a steel cantilever beam and a steel bridge cable. The accuracy and the applicability of the technique will be discussed and commented.

6173-57, Session 13

Health monitoring of sandwich conical shells damaged by impacts using PZT discs, pulse-echo techniques and reference echoes

D. R. Osmont, M. Dupont, D. Barnoncel, ONERA (France)

The sandwich conical shells we are interested in (glass fibers skins and foam core) are very sensitive to low velocity impacts. Such impacts induce debonding between the skins and the core and a crush in the foam which are not visible from the outside. This debonding, under external loads may result in a large delamination and a ruin of the sandwich.

We propose a health monitoring system to localize these damages and estimate their size. This system is based on thin piezoelectric discs bonded on the skins near the base of the conical shell (the only location allowed for the final application) and used as transducers, making it possible to generate and detect guided waves propagating in the conical sandwich. structure

This system has been proven to be efficient for sandwich plates. It is based on the determination of a set of reference echoes Er(t) relative to reference defects (cylindrical holes in the foam) and reference excitations of the structure. Given an echo Ed(t) coming from a damage, it is possible using correlation techniques to determine the reference echo with a "minimum distance" to the given echo. From this particular reference echo it is then possible to obtain an estimation of the damage (size, location).

For plates, the guided waves we use are very simple compared to their analog in conical shells. We show, using simulations, that it is possible to modify the method developed for plates to use it for shells. The reference defects are yet cylindrical echoes in the foam. We show how to construct the base of reference echoes and present applications to the estimation of simulated damages different from cylindrical holes in the foam.

6173-58, Session 13

Quantitative structural health monitoring using acoustic emission

P. D. Wilcox, C. Lee, J. Scholey, M. I. Friswell, M. R. Wisnom, B. W. Drinkwater, Univ. of Bristol (United Kingdom)

Acoustic emission (AE) is well known as a highly sensitive technique to detect various types of damage, such as fatigue crack growth, impacts, delaminations and so forth. This sensitivity coupled with the small number of sensors required potentially makes AE very attractive for structural health monitoring (SHM) applications. AE testing methodology tends to fall into one of two categories: deterministic and probabilistic. In the deterministic methodology, suitable models of the AE process are used to analyse AE data, whereas, in the probabilistic methodology, a variety of techniques are employed to identify empirical trends in experimental data. While the probabilistic approach is well suited to repetitive testing of similar components, it is the belief of the authors that this approach is much less suitable for monitoring limited numbers of complex, high value, safety-critical structures of the type likely to be encountered in SHM. The authors believe that for AE to be used as the basis for an SHM system with quantifiable performance it is necessary have a deterministic model of the complete AE process from source to received waveform.

In the past, the mechanism of AE generation by a variety of sources has been well studied. What has received much less attention due to its inherent complexity is the propagation of these signals through a structure and the mechanism of their detection. In the first part of this paper, progress on the development of a quantitative model for the complete AE process in real structures is presented. The long term goal of the model is to predict the actual AE waveforms received from sensors when any type of AE event occurs anywhere in a structure. To date, the model can predict the waveforms obtained in planar structures from axi-symmetric, out-of-plane Hsu-Neilson (lead break) simulated sources and non-axi-symmetric, in-plane sources of the type associated with fatigue crack growth. The model includes the dispersive, multi-modal propagation of AE signals, their reflection from simple boundaries and their reception by realistic sensors with finite spatial aperture and frequency response. Results from the model are compared to experimental and finite element data.

The second part of the paper considers an alternative strategy for AE signal processing in SHM applications. In many of the most successful applications of AE testing the structure is taken out of service, instrumented and then subjected to a controlled loading cycle during which AE events are monitored. However, in an SHM context the challenge is for a system to detect AE events that occur under normal operating conditions. The environment is therefore likely to be noisy and the challenge is to discriminate between real events and spurious signals due to noise. The traditional AE approach of detecting signals that exceed a predefined threshold level may therefore not be the most appropriate for SHM applications. An alternative is proposed where signals from one or more pairs of sensors are continuously cross-correlated and a rolling average of the cross-correlated signals is recorded. Signals from repeating AE events at the same spatial location will reinforce each other in the cross-correlated average while those from random sources will be suppressed. Source location is performed using the cross-correlated signals from two or more sensor pairs. The technique is demonstrated using simulated and experimental data.

6173-59, Session 13

Structural health monitoring using sparse distributed networks of guided wave sensors

P. D. Wilcox, G. Konstantinidis, B. W. Drinkwater, Univ. of Bristol (United Kingdom)

Guided acoustic waves provide an ideal tool for testing a large structure from a limited number of test locations. Deployable guided wave systems are already routinely used in non-destructive evaluation (NDE) applications for the inspection of geometrically simple one-dimensional waveguide structures such as pipes and rails. In more complex two- and three-dimensional structures, such as airframes, the difficulty in interpretation of signals due to the multitude of reflections from structural features has prevented the development of deployable systems. However, in a structural health monitoring (SHM) context where permanently attached sensors are used, the issue of signal interpretation is potentially surmountable by

using reference signal subtraction. Fundamental to this approach is the sensitivity and stability of the subtraction approach.

In the first part of this paper, strategies for damage detection and location using guided wave SHM systems are reviewed and compared with those in NDE. An important difference between guided wave NDE and SHM systems is that for ease of deployment, the former utilise single sensor units that operate from one location on a structure. Such systems therefore operate in a pulse-echo configuration and the sensor unit (which typically comprises an array of transducers) must achieve a high degree of modal and directional selectivity in order to provide useful information to the operator. Conversely in an SHM system, a distributed network of sensors is needed to achieve structural coverage and this means that both pulse-echo and pitch-catch testing modalities can be employed. Furthermore, the individual sensors can be simple point sources or receivers rather than the complex arrays found in NDE systems. In this part of the paper, the design characteristics of sensors and possible inspection modalities for SHM are investigated. It is shown that, in parallel with a reference signal subtraction algorithm, three distributed point sensors can readily be used to detect and locate damage in a 1 m by 1.5 m by 3 mm thick aluminium plate.

In the second part of this paper, the factors affecting the stability of the reference signal subtraction approach are investigated. Previous work on NDE systems has shown that representative signals from damage are at least 30 dB smaller in amplitude than signals from structural features such as edges. Therefore a reference signal subtraction algorithm must reliably achieve a signal to coherent noise significantly better than this. Experimental studies on a simple test structure will be presented that show that a change in temperature of a few degrees leads to coherent artefacts after subtraction that are of a similar magnitude to the signals arising from defects. Some possible strategies for overcoming this potential barrier to reliable reference signal subtraction are then considered.

6173-60, Session 13

Design, implementation, and comparison of guided wave phased arrays using embedded piezoelectric wafer active sensors for structural health monitoring

L. Yu, V. Giurgiutiu, Univ. of South Carolina

Phased array can interrogate large structural areas from a single location using ultrasonic guided waves generated by tuned piezoelectric wafer active sensors that are permanently attached (embedded) to the structure. Various array parameters determine the array beamforming and steering characteristics. This paper aims to bring up several one or two dimension array designs and research on their beamforming properties and damage detection performance through both analytical simulation and laboratory experiments.

The paper will firstly present the generic guided wave phased array beamforming formulation and explain how the beamforming characteristics are affected by the array parameters such as number of sensors, sensor spacing, and steering angle. Preliminary work of implementing a one dimensional linear phase array is then followed to exemplify how our embedded ultrasonic structural radar (EUSR) scans and detects damage on the plate structures. However, such a linear array has the limitations that it has limited scanning range due to the beamforming directionality deficiency and it can only scan the 0°~180° range either in front of or behind it, i.e., it can not tell if the damage is in the positive or negative direction in the polar coordinates. Hence, we proposed several improved array designs including: (1) a miniaturized array using smaller PWAS; (2) an array using rectangular PWAS; (3) a cross-shaped two dimensional array; (4) a L-shaped two dimensional array. Extensive simulation work has been done to explore the beamforming and beamsteering properties of those arrays. Laboratory experiments have also been conducted to testify the arrays damage detection abilities. The results show that the miniaturized array can look into larger area and be used for damage detection of compact specimen with complicated geometry. Signal rectangular PWAS has directional rather than omnidirectional beamforming which resulting in improved beamforming of the phased array using such PWAS. Two dimensional arrays show directional beamforming within full range of 0° ~ 360° degrees though having limited working steering angles. We finally end up with discussion and conclusion of the arrays and some expectations for future work.

6173-61, Session 13

Self-diagnosis and validation of active sensors used for structural health monitoring

G. Park, C. R. Farrar, Los Alamos National Lab.; F. Lanza di Scalea, S. Coccia, Univ. of California/San Diego

This paper presents a self-diagnostic and sensor validation procedure that performs in-situ monitoring of the operational status of piezoelectric (PZT) materials used for sensors and actuators in structural health monitoring (SHM) applications. The sensor/actuator self-diagnostic procedure, where the sensors/actuators are confirmed to be functioning properly during operation, is a critical component to successfully complete the SHM process with large numbers of active sensors typically deployed in a structure. Both degradation of the mechanical/electrical properties of a PZT transducer and bonding defects between a PZT patch and a host structure could be identified using the proposed procedure. The feasibility of the method was demonstrated by analytical studies and experimental examples, where the functionality of surface-mounted piezoelectric sensors was continuously deteriorated. Furthermore, the temperature effect on the sensor-diagnostics procedure has been experimentally investigated. The proposed sensor diagnostic procedure can provide a metric that can be used to determine the sensor functionality over a long period of service time or after an extreme loading event. Further, the proposed procedure can be useful if one needs to check the operational status of a sensing network right after its installation.

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6174-01, Session 1

Distributed computing strategy for damage monitoring employing

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Recently, rapid advances in smart sensor technology have made damage monitoring using a dense array of sensors feasible, and therefore have the potential to change fundamentally the way civil infrastructure systems are monitored. Indeed, a 2002 National Research Council report noted that the use of networked systems of embedded computers and sensors throughout society could well dwarf all previous milestones in the information revolution. However, few damage monitoring algorithms exist that can allow the distributed computing paradigm offered by smart sensors to be employed for structural health monitoring (SHM). This paper begins with a review of current status of smart sensor technology, indicating some of the challenges and opportunities. Subsequently, a new distributed computing strategy (DCS) for SHM is proposed that is suitable for implementation on a network of densely distributed smart sensors. In this approach, a hierarchical strategy is proposed in which adjacent smart sensors are grouped together to form different communities. A flexibility-based damage detection method is employed to evaluate the condition of the local elements within these communities by utilizing only locally measured information. The damage detection results in these communities are then communicated with the surrounding communities; only the essential information is then sent back to a central station. The efficacy of the proposed strategy is experimentally verified using a 14-bay laboratory-scale truss structure.

6174-02, Session 1

Structural tests using a MEMS acoustic emission sensor

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Our MEMS device was designed and fabricated in 2004 to create a suite of six resonant-type capacitive transducers in the frequency range between 100 kHz and 500 kHz. Each transducer was idealized as a spring-mass system with translational and rocking modes of vibration. Characterization studies showed good comparisons between predicted and experimental electro-mechanical behavior. Acoustic emission events, simulated experimentally in steel ball impact and in pencil lead break tests, were detected and source localization was demonstrated. In this paper we describe the application of the MEMS device in structural testing, both in laboratory and in field applications. We discuss our findings regarding housing and mounting (acoustic coupling) of the MEMS device with its supporting electronics, and we then report the results of structural testing.

In all tests, the MEMS transducers were used in parallel with commercial acoustic emission sensors, which thereby serve as a benchmark and permit a direct observation of MEMS device functionality. All tests involved steel structures, with particular interest in propagation of existing cracks or flaws. A series of four laboratory tests were performed on beam specimens fabricated from two segments (Grade 50 steel) with a full penetration weld (E70T-4 electrode material) at midspan. That weld region was notched, an initial fatigue crack was induced, and the specimens were then instrumented with one commercial transducer and with one MEMS device; data was recorded from five individual transducers on the MEMS device. Under a four-point bending test, the beam displayed both inelastic behavior and crack propagation, including load drops associated with crack instability. The MEMS transducers detected all instability events as well as many or most of the acoustic emissions occurring during plasticity and stable crack growth. The MEMS transducers were less sensitive than the commercial transducer, and did not detect as many events, but the normalized cumulative burst count obtained from the MEMS transducers paralleled the count obtained from the commercial transducer. Waveform analysis of signals from the MEMS transducers provided additional information concerning arrivals of P-waves and S-waves. Similarly, the analysis provided additional confirmation that the acoustic emissions emanated from the damage zone near the crack tip, and were not spurious signals or artifacts.

Subsequent tests were conducted in field applications where the MEMS transducers were redundant to groups of commercial transducers. Application examples included vessels under test pressure and gusset plates in truss bridge construction under passage of heavy traffic loads. The MEMS transducers were found to be functional, but were less sensitive in their present form than existing commercial transducers. We conclude that the transducers are usable in their current configuration and we outline applications for which they are presently suited, and then we discuss alternate MEMS structures that would provide greater sensitivity.

6174-03, Session 1

Environmental testing of wireless sensor system for structural health monitoring of civil infrastructure

K. D. Janoyan, E. S. Sazonov, R. Jha, M. Fuchs, K. Cross, V. Krishnamurthy, Clarkson Univ.

Presented in this paper is the environmental testing of Wireless Intelligent Sensor and Actuator Network (WISAN) currently under development at Clarkson University for the use of long-term structural health monitoring of civil infrastructure. The wireless sensor nodes will undergo controlled mechanical vibration and environmental testing in the laboratory. A temperature chamber will be used to perform temperature cycle tests on the sensor nodes. The temperature chamber will also houses a small shaker capable of introducing mechanical loading under the controlled temperature cycle tests. At low temperatures, the resistance of the electronics processing and storage characteristics will be studied. Also, the testing will look at volume expansion and degradation of characteristics due to freezing, degradation of functions and performance, and mechanical characteristics caused by contraction. At high temperatures, temperature-related changes in sensor nodes due to excessively high temperatures will be investigated. Also studied will be the effects of temperature cycles, including the thermal stresses induced in the nodes and housing and the distortion caused due to expansion and contraction, fatigue, cracks, and changes in electrical characteristics due to mechanical displacement. And finally, mechanical vibration loading will be introduced to the WISAN sensor nodes. Mechanical looseness, fatigue destruction, wire disconnection, damage due to harmonic vibration, defective socket contact, joint wear, destruction due to harmonics, lead breakage, occurrence of noise and abnormal vibration, cracking will be monitored. The eventual goal of the tests is to verify WISAN's performance under anticipated field conditions in which the sensors will be deployed.

6174-150, Session 1

Wearable sensors for human health monitoring

H. H. Asada, Massachusetts Institute of Technology

Wearable sensors for continuous monitoring of vital signs for extended periods of weeks or months are expected to revolutionize healthcare services in the home and workplace as well as in hospitals and nursing homes. In this invited talk the state-of-the-art of wearable monitoring technology and its clinical applications will be described along with their socio-economical impacts. First, a wearable blood pressure sensor and other novel sensors for cardiovascular, pulmonary, and diabetes patients will be presented. Technical issues, including motion artifact reduction, power saving, and wearability enhancement, will be addressed. Second, sensor fusion and sensor networking for integrating multiple sensors with diverse modalities will be discussed for comprehensive monitoring and diagnosis of health status. Unlike traditional snap-shot measurements, continuous monitoring with wearable sensors opens up the possibility to treat the physiological system as a dynamical process. This allows us to apply powerful system dynamics and control methodologies, such as adaptive filtering, single- and multi-channel system identification, active noise cancellation, and adaptive control, to the monitoring and treatment of highly complex physiological systems. A few clinical trials illustrate the potentials of the wearable sensor technology for future heath care services.

6174-151, Session 1

Sensors and sense in structures

M. A. Sozen, Purdue Univ.

Given the colossal investment in the infrastructure, it is a mystery that the condition of almost all of it remains a mystery to those who build and maintain it. There appear to be two hurdles slowing quick and pragmatic prognosis and diagnosis

of the infrastructure. One is the lack of familiarity of those who build and maintain with the opportunities in the rapidly expanding sensor possibilities. The other is again the lack of familiarity of those who specialize in sensors with the problems encountered in the infrastructure.

There needs to be strong interaction among the disciplines for society to benefit from the promise of inexpensive and durable sensor systems. The types of information and network protocols required to promote timely prognosis and diagnosis will be discussed with examples of tools that are currently in range and examples of those that are not yet in range.

6174-04, Session 2

Prospective energy densities in the forisome: a new smart material

A. Shen, W. Pickard, Washington Univ. in St. Louis

The forisome is a protein structure of plants which, in low Ca2+ solutions, assumes a crystalline condensed conformation and, at high Ca2+, swells to a dispersed conformation; this transition has been attributed to electrostatic deformation of protein “modules”. Forisomes could become an important smart material if the energy density of transformation exceeds 0.5 MJ m-3 . Quantitation of the forisome as a charged porous continuum permeated by electrolyte fails by orders of magnitude to achieve this energy density electrostatically. However, condensed to dispersed transitions can be visualized alternatively: (i) an ionic bond near the surface of a forisome crystal dissolves to produce two bound surface charges; (ii) the anionic site bonds to Ca2+ becoming less negative; (iii) the two sites repel each other and move apart drawing in water; (iv) electrolyte anions are attracted, bringing with them bound water; (v) this transition propagates throughout the crystal, with incompressible imbibed electrolyte stabilizing the initial separation. With the above transition sequence, it is possible to achieve an energy density of 0.5 MJ m-3 if the “modules” in the crystal are roughly 10 nm on a side.

6174-05, Session 2

Interdigitated PVDF transducer for flaw detection

H. Gu, M. L. Wang, Univ. of Illinois at Chicago

Since the recognition of the advantages of using Lamb Waves in nondestructive testing (NDT), Lamb Waves and other guided waves have attracted more and more attention nowadays. Unlike waves used in conventional ultrasonic inspection, such as bulk longitudinal and shear waves, which propagate in the region of structure immediately around the transmitting transducer, Lamb Waves can propagate over a long distance. Previously in our work, interdigitated PVDF transducers for generating surface acoustic waves have been built by using photolithography technology. These sensors have been tested to be able to excite and receive Lamb Waves successfully.

In propagating through solid materials, acoustic waves may have velocities that are dependent on their frequency. In this case, Fast Fourier Transform (FFT) may not be good enough to interpret all the information included in a received signal. As a result, people are spending a lot of energy on Time-Frequency Representations (TFRs), in which both frequency and time information can be obtained at the same time. Among these TFRs, the reassigned spectrogram has been reported to be the most widely spread in detecting different modes in Lamb Waves.

As an extension from previous work, this paper focuses on the implementation of interdigitated PVDF sensors on some steel plates with flaws. Experiments have been conducted, and efforts have been spent on identifying the locations of the flaws. The reassigned spectrogram was employed during signal processing and analysis.

6174-06, Session 2

Piezoresistive feedback for decreased response time of MEMS thermal actuators

R. Messenger, T. McLain, L. Howell, Brigham Young Univ.

Thermal actuators have demonstrated great utility in the MicroElectroMechanical Systems (MEMS) environment. They have smaller footprints, greater reliability, and larger output forces than other MEMS actuator technologies. One potential thermal actuator drawback is slower response times due to the thermal processes involved. A promising solution is the application of high-gain feedback control. The application of feedback control to MEMS has typically been hampered by a lack of reliable and inexpensive sensing technology to monitor the system. Capacitive sensing has reliability and signal-to-noise issues while optical sensors, such as laser dopler vibrometers, are costly and large.

In this study the inherent piezoresistivity of polycrystalline silicon, of which the MEMS are fabricated, is used as the transducer mechanism. Flexures are attached to the actuator so that they are forced into compression as the actuator displaces. As the piezoresistive flexures are stressed their resistance increases. By configuring the flexures as a Wheatstone bridge, the system outputs a voltage that is proportional, in a nearly linear fashion, to the displacement of the actuator. This is all accomplished with simple and reliable mechanisms. The output signal has a sufficient signal-to-noise ratio that the signal processing and control implementation can be accomplished with a simple off-chip circuit.

A complication arises from the connection between the actuator and the sensing flexures. It is not possible to mechanically connect and electrically isolate the flexures and the actuator. This causes the signal driving the actuator to corrupt the output of the sensor. By using a floating power supply to excite the Wheatstone bridge and a common-mode-rejection scheme, the driving signal is filtered out of the sensor output.

A linear lumped-element model of the actuator is used for control design. Analysis suggests that the system poles can be shifted to significantly faster regions of the complex plane using simple proportional feedback control. Because the open-loop system is dominated by distinct real poles, and because the sensor output has a high signal-to-noise ratio, large feedback gains can be used without causing stability or noise problems.

Two devices were manufactured using the MUMPS and SUMMiT fabrication processes. The signal processing and control implementation were accomplished using off-the-shelf analog components. Experimental results from both devices are presented demonstrating the decrease in response time achieved through piezoresistive feedback control.

6174-07, Session 2

Modeling and optimization of a side-implanted piezoresistive shear-stress sensor

Y. Li, Univ. of Florida; M. Papila, Sabanci Univ. (Turkey); T. Nishida, M. Sheplak, Univ. of Florida

We present the design optimization of a micromachined floating element piezoresistive shear stress sensor for direct, quantitative measurement of time-resolved, fluctuating wall shear stress. To accurately capture the spectrum of the turbulent shear-stress fluctuations, the device must possess a large usable bandwidth, and the spatial dimensions of the device must be less than the smallest turbulent structures of interest to avoid spatial filtering. The cost function, minimum detectable shear stress (MDSS) is formulated in terms of sensitivity and noise floor, and is subjected to constraints of geometry, linearity, bandwidth, power, measurable noise floor and resistance. The optimization results indicate that the optimal device performance is improved with respect to existing shear stress sensors, with a minimum detectable shear stress of and dynamic range greater than .

Previous researchers have investigated microelectromechanical systems (MEMS) floating element shear stress sensors[1-7], which directly measure the integrated shear force produced by shear stress on the flush-mounted movable “floating” element. Several transduction schemes exist to detect the mechanical response of the floating element, including capacitive[1,2,6] , piezoresistive [3, 4] and optical techniques[5,7]. These sensors suffer from sensitivity drift, limited bandwidth or an unacceptably high minimum detectable signal (MDS). To overcome these limitations, we employ a side-implanted piezoresistive sensing scheme to obtain large bandwidth and low MDS.

The sensor structure integrates shadow side-implanted diffused resistors into the element tethers for piezoresistive detection. In this transduction scheme, the integrated force produced by the wall shear stress on the floating element causes the tethers to deform and thus creates a mechanical stress field in the tethers. The piezoresistor responds to the mechanical stress field with a change in resistance from its nominal unstressed value. The conversion of the shear-stress induced resistance change into an electrical voltage is accomplished by configuring the piezoresistors into a fully-active Wheatstone bridge.

A nonlinear mechanical model is combined with piezoresistive electromechanical model to determine the electromechanical sensitivity. Lumped element modeling (LEM) is used to estimate the resonant frequency. Finite element modeling (FEM) is employed to verify the mechanical models and LEM results. Two dominant noise source, noise and thermal noise were considered to determine the noise floor. These models were then leveraged to obtain optimal sensor designs for several specification sets. Considering the tradeoff of the sensitivity and electronic noise floor in optimizing the performance, all design problems are formulated to find the optimum dimensions of the floating element and tethers, geometry and surface doping concentration of piezoresistors, and bias voltage. The optimization problem was implemented in MATLAB(r) using its optimization toolbox that employs

sequential quadratic programming for non-linear constrained problems and calculates the gradients by finite difference method.

Uniform doping was assumed in the optimization, and then non-uniform doping profile using FLOOPS(r) simulation is applied to obtain the final performance. Resistance and piezoresistive sensitivity for non-uniform doping are derived involving stress averaging and conductance weighted piezoresistance coefficient. The results indicated that the non-uniform doping has about 5dB dynamic range decrease.

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6174-08, Session 2

Piezoelectric wafer active sensor impedance analysis for structural health monitoring

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Structural health monitoring (SHM) is important for reducing maintenance costs while increasing safety and reliability. Piezoelectric wafer active sensors (PWAS) used in SHM applications are able to detect structural damage using Lamb waves. PWAS are small, lightweight, unobtrusive, and inexpensive. PWAS achieve direct transduction between electric and elastic wave energies. PWAS are essential elements in the Lamb-wave SHM with pitch-catch, pulse-echo, phased array system and electromechanical impedance methods.

This paper starts with a literature review of the state of the art on the impedance method for PWAS applications. Then, impedance model for free and bonded PWAS with different sizes and shapes will be given. Experiments showed that the real part and imaginary part of PWAS had different usage. Applications of impedance-based structural health monitoring indicate impedance method as a good candidate for damage detection and sensor durability verification for SHM smart sensor.

6174-09, Session 3

Bending of iron-gallium (Galfenol) alloys for sensor applications

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Galfenol alloys (Fe100-x Gax) have been shown to combine significant magnetostriction (~400 ppm) with strong mechanical properties (tensile strengths ~500 MPa), making them well suited for use in robust actuators and sensors as an active structural material. A variety of projects are in development to utilize this material in novel magnetostrictive applications, one of which calls for electro-chemically deposited Galfenol nanowires to be acoustically excited into bending. In order to properly design this system, this project investigates the magnetomechanical behavior of cantilevered Galfenol beams to applied bending loads at the macro to nanoscale. A series of experiments are conducted to verify that the material is mechanically sound as well as magnetically active in this novel loading configuration. Mechanical excitation is applied to the tip of each beam and the magnetic response of the samples are measured with a giant magnetoresistive (GMR) sensor located behind the beam and a pickup coil wound directly on each rod. Analytically, the system is accurately modeled using both the linear constitutive equations with coefficients fit from experimental magnetization vs. stress data as well as a nonlinear free energy model. Initial research has begun into the effect of scaling the system down to nanometer lengths. Individual Galfenol nanowires are to be characterized through high frequency excitation in a scanning electron microscope (SEM), quasi-static bending with an atomic force microscope (AFM) tip mounted onto a nanomanipulator system, and magnetic moment orientation data from magnetic force microscopy (MFM). Additional work includes attempting acoustic excitation of entire cantilevered nanowire arrays.

6174-10, Session 3

Stochastic adaptive sensor modeling and data fusion

M. Kumar, Duke Univ. and U.S. Army Research Office; D. P. Garg, Duke Univ.; R. Zachery, U.S. Army Research Office

The primary goal of a multi-sensor system is to combine information from a multitude of sources in a coherent and synergistic manner to obtain a robust, accurate and consistent description of quantities of interest in environment. There are several issues that arise when fusing information from multiple sources. The most fundamental issue is that sensors providing measurements include inherent uncertainties. The uncertainties in sensors not only arise from the impreciseness and noise in the measurements, but are also caused by the ambiguities and inconsistencies in the environment, and inability to distinguish between them. The strategies used to fuse data from these sensors should be able to eliminate such uncertainties, take into account the environmental parameters that affect sensor measurements, and fuse different types of information to obtain a consistent description of the environment.

This paper advances the development of sensor models based on a probabilistic approach that could accurately provide information about individual sensor's uncertainties and limitations. The sensor model aims to provide a most informative likelihood function that can be used to obtain a statistical and probabilistic estimate of uncertainties and errors due to some environmental parameters or parameters of any feature extraction algorithm used in estimation based on sensor's outputs. A probabilistic sensor model is particularly useful because it facilitates the determination of the statistical characteristics of the data obtained. This probabilistic model is usually expressed in the form of a probability density function (p.d.f.) $p(z \mid x)$ that captures the probability distribution of measurement by the sensor (z) when the state of the measured quantity (x) is known. This distribution is extremely sensor-specific and can be experimentally determined. In order to automatically and intelligently learn the dependence of environmental factors on sensor readings, this paper makes use of a neural network trained with the help of a novel technique that obtains training signal from a maximum likelihood estimator.

One of the major problems in sensor fusion is that sensors frequently provide spurious observations which are difficult to predict and model. Most of the experimentally developed models make use of data which are not spurious, and represent uncertainties arising only from sensor noise and inherent limitation. Fusing spurious observation with the correct one often leads to inaccurate estimation. Hence, sensors providing spurious measurements should be eliminated before fusing with other measurements. However, it is not an easy task to predict if a particular sensor would provide spurious measurement or even to identify if measurement from particular sensor is inaccurate. Most of the fusion strategies based on Bayesian approach available in literature handle inconsistency in data rather poorly. This paper makes use of Bayesian approach for fusion that takes into account measurement inconsistency and entropy to identify spurious data. Based on entropy of the posterior distribution of desired quantity, the approach presented in this paper detects if the data from sensors are spurious or inconsistent. Entropy based analysis helps in determining if the fusion of data from particular sensor actually improves the information content of fused variable. Hence, the proposed method can also be used effectively for appropriate sensor selection. The analytical strategy presented in this paper was verified using extensive simulations and validated via experiments performed using stereo vision sensors and IR/Laser proximity sensors in a robotic workcell available in the Robotics and Manufacturing Automation (RAMA) Laboratory at Duke University.

6174-11, Session 3

UV-induced intrinsic Fabry-Perot interferometric sensors and their multiplexing for temperature and strain sensing

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We present UV-induced intrinsic Fabry-Perot interferometric (IFPI) fiber sensors and a frequency-division-multiplexing (FDM) scheme for quasi-distributed tem-

perature and strain sensing. We introduce a fabrication system for UV-induced reflectors and IFPI sensors and present a spectrum-based measurement system with a swept laser source to measure the fringe patterns of IFPI sensors. The FDM scheme is based on the multiplexing of sub-carrier frequencies generated by a frequency-modulated continuous-wave (FMCW) technique. IFPI sensors with different optical path differences (OPD) will have different sub-carrier frequencies. We use band pass filters to select individual frequency component and use frequency-estimation based signal processing algorithms to determine the OPD of each sensor. Experimental results for multiplexed temperature and strain sensing are demonstrated. The performance of the multiplexing system is discussed.

6174-12, Session 3

Scheduling policies of intelligent sensors and sensor/actuators in flexible structures

M. A. Demetriou, R. Potami, Worcester Polytechnic Institute

In this note, we revisit the problem of actuator/sensor placement in large civil infrastructures and flexible space structures within the context of spatial robustness. The positioning of these devices becomes more important in systems employing wireless sensor and actuator networks (WSAN) for improved control performance and for faster failure detection. The ability of the sensing and actuating devices to possess the property of spatial robustness results in reduced control energy and therefore the spatial distribution of disturbances is integrated into the location optimization measures. In our studies, the structure under consideration is a flexible plate clamped at all sides. First, we consider the case of sensor placement and the optimization scheme attemps to produce those locations that minimize the effects of the spatial distribution of disturbances on the state estimation error; thus the sensor locations produce state estimators with minimized disturbance-to-error transfer function norms. A two-stage optimization procedure is employed whereby one first considers the open loop system and the spatial distribution of disturbances is found that produces the maximal effects on the entire open loop state. Once this “worst” spatial distribution of disturbances is found, the optimization scheme then finds the locations that produce state estimators with minimum transfer functions. In the second part, we consider the collocated actuator/sensor pairs and the optimization scheme produces those locations that result in compensators with the smallest norms of the disturbance-to-state transfer functions.

Going a step further, an intelligent control scheme is presented which, at each time interval, activates a subset of the actuator/sensor pairs in order provide robustness against spatiotemporally moving disturbances and minimize power consumption by keeping some sensor/actuators in sleep mode.

6174-13, Session 3

Chemo-mechanical sensors based on freestanding polymeric structures

M. R. Begley, J. P. Landers, Univ. of Virginia

This talk will describe polymeric chemical sensors that strongly couple selective surface adsorption to mechanical deformation. A complete theoretical framework for adsorption-induced deformation is used to identify devices that amplify the effects of surface adsorption via mechanical instabilities (i.e.,buckling). This facilitates optical and electronic transduction approaches that can be integrated with lab-on-a-chip technology. The talk will describe three parallel research efforts: (i) surface functionalization of polymers - surface treatments will be identified which make PDMS chemically-selective for specific target molecules, (ii) microfabrication of freestanding polymeric ultra-compliant structures which experience large deformation upon adsorption, and (iii) optical transduction - creating microchip devices with integrated transduction features. The established theoretical framework is used to directly quantify microdevice performance in terms of surface adsorption, microscale deformation, and thermomechanical properties.

6174-14, Session 3

Novel application of a magnetoelastic sensor as a NDE tool to detect and monitor corrosion in structural steels

E. Indacochea III, F. A. Rumiche, M. L. Wang, Univ. of Illinois at Chicago

Magnetoelastic sensors are being used extensively as a non destructive evaluation (NDE) technique for sensing stress levels in civil engineering applications. The present work focuses on the possibility of using these sensors as a NDE tool for corrosion assessment in structural steels. Four steels commonly used in civil engineering structures were evaluated. The variation in magnetic properties registered with the magnetoelastic sensor for non corroded and corroded samples has been correlated with the extent of corrosion. It was found that the magnetic induction decreases as corrosion increases. Furthermore, particular variations in permeability and coercivity for each steel have been correlated with the degree of damage. The magnetic property variations in corroded samples are attributed to the presence of corrosion films and products with varied magnetic behavior and surface morphology alterations. The corrosion films and products have been characterized using X-Ray diffraction and Electrochemical Impedance Spectroscopy. The surface morphology was evaluated by optical and scanning electron microscopy. This work proposes correlation curves to quantify the extent of corrosion in terms of mass loss according to the magnetic response for each material. It was possible to detect mass losses due to corrosion as low as 0.5 %. Therefore magnetoelastic sensors have the potential to be used effectively as NDE tool not only to assess corrosion, but also to detect it at early stages and monitor its development.

6174-15, Session 4

Evaluation of corrosion damage in steel-reinforced mortar using guided waves

H. L. Reis, B. Ervin, D. A. Kuchma, J. T. Bernhard, Univ. of Illinois at Urbana-Champaign

A major cause of structural damage to our aging reinforced concrete infrastructure is corrosion of the reinforcing steel bars. While many nondestructive methods have been proposed for use in early detection of reinforcement corrosion, no single detection method has proven robust enough to solve the problem entirely. Typically, there is a need to know whether there is corrosion activity, how much corrosion activity has occurred, at what rate it is occurring, and the location of the activity. Thus, there is a need for a new testing procedure.

Towards the development of a wireless embedded sensor system to monitor and assess corrosion damage in prestressed concrete girders, mechanical waveguide testing on reinforced mortar specimens has been carried out while the specimens undergo accelerated corrosion using impressed current. The mechanical guided wave testing takes advantage of the geometry of the rebar embedded in concrete. While previous experiments have shown promise with the fundamental flexural propagation mode, current testing results are presented for the fundamental longitudinal propagation mode. To illustrate the emphasis of different frequencies as the reinforced mortar specimens accumulate corrosion damage, the fundamental longitudinal mode was invoked and a frequency sweep was used. Waveform energy (indicative of attenuation) at the different frequencies is presented and discussed in terms of corrosion damage. Current results indicate that the loss of bond strength between the reinforcing steel and the surrounding concrete can be detected and evaluated.

6174-16, Session 4

Monitoring fresh concrete using guided waves

H. L. Reis, J. L. Borgerson, Univ. of Illinois at Urbana-Champaign

The evaluation of fresh concrete is critical for reducing the time needed for construction and rehabilitation of existing concrete structures. Ultrasonic characterization of fresh concrete has been difficult because of its relative high attenuation. In this study, a guided wave approach is used to measure the energy loss of the first torsional wave mode from a circular steel bar to the surrounding mortar. Three piezoelectric shear transducers with a center frequency of 250 kHz were used; two were used as senders to generate the torsional wave mode, and the third was used as the receiver. Using this through-transmission system, the evolution of the mortar properties over the first twenty-four hours of hydration were correlated with the attenuation of the guided wave.

It was observed that the approach was useful for monitoring the curing rate and the microstructure development of varying water-to-cement ratios (w/c = 0.40, 0.50, and 0.60). In addition, the effects of admixtures (accelerant and retardant) on the decay of the guided wave were also explored. It was shown that the mixtures with a low water-to-cement ratio or an accelerant caused a rapid decay in the torsional wave due to the faster curing rates. Conversely, mixtures with a high water-to-cement ratio or a retardant resulted in a slow decay of the guided wave.

6174-17, Session 4

Nondestructive inspection of a lead rubber bearing using ultrasonic wave

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The purpose of this study is to evaluate the internal state of a Lead Rubber Bearing (LRB) using ultrasonic waves. The LRB is used as an earthquake isolation device which is made from layers of rubber sheets sandwiched together with layers of steel plates. In the middle of the bearing is a solid lead plug. The seismically

isolated structure with LRBs is very stiff and strong in the vertical direction, however it is flexible in the horizontal direction. The lead plug reduces the kinetic energy by converting the energy into heat. It is helpful to decrease and eventually cease the building's vibration in a shorter time. Nondestructive inspection using ultrasonic waves has recently emerged as an important inspection technique capable of resolving inspection problems that contemporary methods struggle with such as cracks in metallic structures. Though the LRB is very important component in seismically isolated structure, some of internal states are unknown yet. Thus, we prepared two kinds of miniature LRB models and excited them by ultrasonic transducers or AE sensors. One miniature LRB model has normal lead damper; the other has abnormal one. The output signals obtained from the inside are different for each model. Infinite number of routes are assumed as ultrasonic wave propagation line. However, in this examination, we found the major powers come from the route in the steel layers. Therefore, considering this propagation route, we could succeed in evaluating internal state of LRB by using ultrasonic waves.

6174-18, Session 4

Damage detection of civil infrastructures with piezoelectric oscillator sensors

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Many researches have been reported on the condition monitoring of civil infrastructures by means of piezoelectric sensors. Most of them made use of the impedance change of the piezoelectric device in relation to the creation of internal damages to the structure. The impedance measurement is a well accepted method in the piezoelectric sensor area, and has been proved by many authors to be useful for civil structure diagnosis. However, the impedance measurement normally requires sophisticated equipment and analysis technology. For more general and wide application of the piezoelectric diagnosis tool, a new methodology is desired to overcome the limitations of the existing technology, i.e. impedance measurement. This paper presents the feasibility of a piezoelectric oscillator sensor to detect the damages in civil infrastructures. The oscillator sensor is composed of an electronic feedback oscillator circuit and a piezoelectric thickness mode vibrator to be attached to the structure of interest. Damage to the structure causes a corresponding change of the impedance spectrum of the structure, which results in a corresponding change of the resonant frequency of the system. The oscillator sensors can instantly detect the frequency change in a very simple manner. Feasibility of the piezoelectric oscillator sensor was verified in this work with a sample aluminum plate where artificial cracks of different depth were imposed in sequence. Validity of the measurement was confirmed through comparing the experimental data with the results of the finite element analysis of the plate with cracks. Performance of the oscillator sensor was also compared with that of its conventional counterpart, i.e. impedance measurement, to manifest the superiority of the oscillator sensor.

6174-19, Session 4

Modified one-sided stress wave velocity measurement technique for concrete NDT & E

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Ultrasonic wave velocity method has been used successfully to evaluate the quality of concrete for over 60 years. Recently, researches concerning one-sided stress wave velocity measurements have been studied with the measurement of Rayleigh wave (R-wave) in concrete in addition to longitudinal wave (L-wave) to overcome the limitation of L-wave velocity method that requires the accessible opposite sides of the structure for in situ through-thickness measurements. In all of the recent research, the arrival of the L-wave is taken to be the first disturbance above a given threshold detected by each receiver and the time difference between these arrivals allows for L-wave velocity determination. However, Jones et al. suggested that L-wave velocities measured in this one-sided manner are consistently underestimated due to pulse dispersion. The threshold arrival detection method that is used in all of approaches does not account for pulse dispersion only except Popovics et al. On the other hand, the R-wave velocity is determined by the cross-correlation technique, the difference in the phase spectra, or the time difference between the first significant sharp peaks in the time domain signals of each receiver. Those methods were assumed that concrete behaves as a linear, elastic and isotropic solid and hence R-wave velocity does not change in transit between transmitter and receiver. However, a laboratory and numerical experiment of the previous researcher show multiple scattering of elastic waves from heterogeneities near the surface not only attenuates, but also delays coherent events. Therefore, in order to effectively use surface waves for nondestructive testing or evaluation of concrete structures, techniques to determine velocity reflecting heterogeneity in concrete must be employed.

In this study, modified stress wave velocity measurement technique is developed to obtain from one-sided measurements. R-wave velocity measurement technique using continuous wavelet transform (CWT) to reflect scattering effects is discussed. L-wave velocity determination procedure based on the measured R-wave velocity is explained. And then experiments are conducted on the variety of concrete specimen to validate the proposed technique. The proposed technique is distinct from that of earlier researchers. To show this, experimental study is performed to demonstrate the effectiveness of the proposed technique compared with conventional one-sided techniques.

6174-20, Session 5

Structural vibration control of civil structure with squeeze-mode smart damper; experimental comparisons

G. Heo, Konyang Univ. (South Korea); J. Joon-Ryong, L. Giu, W. Lee, H. C. Shin, Chungnam National Univ. (South Korea)

This paper experiments on each of three control algorithms which are adapted into an unified control algorithm in order to decide on the best smart damping system for semi-active control in civil structures using squeeze mode smart damper. These algorithms are Lyapunov algorithm, clipped optimal algorithm, and bang-bang algorithm, all of which are superior in efficiency and reliability to any existing semi-active control algorithms. Such adaptation makes it easier to develop control algorithm because it shows continuous and discrete time at the same time, and to analyze the control characteristics in the case of broadly distributed natural frequency by securing enlarged stable regions. In order to prove its validity, we performed vibration control tests using a prototype steel plate girder bridge. Since the model is a reduced one, we also scaled El Centro earthquake wave to the same scale as the reduced model bridge. Various performance indexes have been used to see which algorithm is most effective in control. Also, other experiments were performed to define the control characteristics which would enable us to see how all control conditions—displacement control, force control, and acceleration control—work with each control algorithm. Those experiments showed that each control algorithm works differently according to each different control condition. Among each algorithm, it is found that Lyapunov algorithm is the most effective for semi-active control in the unified control system. Therefore, it is necessary to design a control system according to structural conditions and circumstances.

6174-21, Session 5

Study of hierarchical decentralized vibration control of structures

Q. Zhou, Z. Duan, Harbin Institute of Technology (China)

Since the concept of structural control was proposed by J.P.T. Yao, tremendous progress has been made over the last three decades toward making active structural control a viable technology for enhancing structural functionality and safety against natural hazards such as strong earthquakes and high winds. However, because of the high dimensionality and multiple-input-multi-output nature of civil structure model, it is difficult to design a control strategy to achieve desired stability, robustness with centralized control method.

Hierarchical decentralized control strategy is employed in this paper in response to this difficulty. In this approach, the structure to be controlled is divided into a set of substructures. A hierarchical decentralized control consists of two levels: the low-level subsystem by which each substructure is controlled independently by local controllers and local information, and the high-level system that we call it global control system, which takes the outputs of every substructure as its input, and eliminates interconnection among substructures.

With LQR active control algorithm in Matlab environment, the centralized control and hierarchical decentralized control strategy is implemented on a cantilever beam under dynamic excitation. Simulated results show that both the centralized control and hierarchical decentralized control are able to control the vibration of cantilever. Compared with centralized control, hierarchical decentralized control method has a good control effect with preferably suppressed displacement response and less control force. The study in this paper presents a promising technology for structural vibration control.

6174-22, Session 5

MR damper-based smart passive control system for seismic protection of building structures

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The control performance of the magnetorheological (MR) damper-based smart passive control system for seismic protection of building structures has been experimentally investigated. In the proposed system, an electromagnetic induction (EMI) part composed of a permanent magnet and a coil is introduced in order to make the control system more compact, simple, and economic. The EMI part converts the kinetic energy of the relative motion between a structure and a damper into the electric energy according to the Faraday law of induction, resulting in the change of damping characteristics of the MR damper. Hence, the conventional MR damper-based semiactive control system including a controller, sensors, and a power source can be replaced with much more simple system consisting of the MR damper and the EMI part. The proposed system is passively operated, but it has adaptability to excitations such as earthquakes because the induced current generated from the EMI part, which is a command input to the MR damper, is proportional to input loads. To verify the effectiveness of the smart passive control system, a shaking table test using a small-scale building model employing the MR damper with the EMI part has been carried out. The control performance of the smart passive control system has been compared with conventional MR damper-based semiactive control systems employing several control algorithms such as clipped-optimal control and fuzzy logic-based control algorithms.

6174-23, Session 5

Wind-vibration intelligent control in high-rise structures with installed MR dampers by genetic algorithm

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Wind load has made great effects on high-rise structures and made serious damages of human's life and properties. The paper focuses on the problem of wind-induced vibration multi-responses of high-rise buildings. So smart MR dampers are used to control and reduce the responses.

Firstly, based on the characteristic of wind load and Davenport wind speed power spectrum as well as Shinozuka theory, the time history of pulse wind velocity and pressure of the building has been simulated by superposition of harmonic waves method.

Additionally, the method to analyze wind-direction induced nonlinear multi-oscillation in the time domain is established. The dynamic model and equation of motion of the structural system are firstly set up and the parameters are determined also.

Thirdly, the BINGHAM model of MR damper is elected and a control strategy called 'on-off' semi-active control strategy using prep LQR arithmetic is also put forward in this paper. The strategy makes force of MR dampers equal to LQR force of active control strategy. An optimal installation model of structure based on genetic algorithm is set up in order to install MR dampers economically. A few of weight coefficients for safety and economy are induced, so variety of installation plans is derived numerically for the different standard levels. Using genetic algorithm optimal box of scientific compute software Matlab and structure comfort aim function, the optimal placement of MR damper is discussed.

Finally, in order to illustrate the simulating procedures, a 12-story reinforced concrete frame structure is used numerically as an example to show the optimal steps and main ideas, and the optimal placement schemes are suggested. The wind load is simulated numerically by considering both the wind direction of southeast or northwest and three kinds of wind that their magnitudes of the wind speed are the ones happened probably in 10, 50 and 100 years, respectively. The results of calculation indicated that this method could reduce efficiently the structural vibration multi-response. The method of genetic algorithm can be used effectively and economically in the optimal installation design of MR dampers in high-rise buildings to decreases the structural vibration responses.

6174-24, Session 5

A smart passive damping system for stay cables

S. Cho, The Univ. of Western Ontario (Canada); J. Koo, Miami Univ.; J. Jo, POSCO Technical Research Labs. (South Korea)

Stay cables, such as used in cable-stayed bridges, are prone to vibration due to their low inherent damping characteristics. Several methods have been proposed and implemented to mitigate this problem, though each has its limitations. Recently some studies have shown that semiactive control systems using Magnetorheological(MR) dampers and active control systems can potentially achieve higher performance levels and adaptability with few of the detractions as compared their passive counterparts. However, most semi-active and active control systems that use MR dampers require additional power supplies, controllers, and sensors, adding complexity into the system. The complexity may not be desirable to effectively control many large civil structures, such as high-rise buildings. This paper proposes a novel smart passive damping system with MR dampers. The smart passive device includes an electromagnetic induction (EMI) system to power the MR damper. The numerical study considered [put a model her, for example three story building] to evaluate the dynamic performance of the smart passive damping system for mitigating the vibration of stay cables. Moreover, the performances of the smart passive damping system are compared with those of an equivalent linear viscous damper and an MR damper operated in a pssive-mode.

6174-25, Session 5

Experimental investigation on vibration control of one stay cable by using magnetorheological fluid dampers

M. Liu, H. Li, Harbin Institute of Technology (China)

In the past few decades, cable-stayed bridges have found wide applications throughout the world. Due to the slenderness and the very low internal damping, cables are prone to vibration. Unacceptable oscillations of the cables in cable-stayed bridges have appeared on several occasions. Passive control of cables using viscous dampers attached transversely to the cables is demonstrated to be more effective and practicable. An optimal damper size exists and the maximum supplemental damping ratio can provide sufficient damping for short cables. But the passive linear viscous dampers cannot provide enough supplemental damping to eliminate the long cables vibration. Magnetorheological Fluid (MR) dampers have been proven to be effective in many applications and can potentially achieve performance levels almost the same as comparable active devices, and demonstrated the efficacy of MR dampers as an alternative to mitigate cable vibrations.

One stay cable model, which is 14m long with inclined angle being 30 degree is set up to investigate vibration control of one stay cable by using MR damper, in the Structure Laboratory in Harbin Institute of Technology, in China. The MR damper is fabricated by the research group with a maximum stroke of ±10mm, and a peak-to-peak force on the order of 45N without any applied current and of 90N with a maximum applicable current intensity of 0.3 Amp. The relationships of damping force and applied current, damping force and damper displacement, and damping force and damper velocity were obtained through a performance test under sinusoidal excitation with the amplitude of 3mm and a frequency of 3.46Hz.The performance test is conducted in a MTS 810 at Harbin Institute of Technology.

The frequencies and modal damping ratios of the first three models of the unimpeded tested cable are obtained through the relationship curves of frequency to amplitude, respectively. And then, a series of tests under sinusoidal excitation with the first modal frequency are carried out to investigate the control efficacy of cable vibration achieved by "Passive-off" MR dampers and "Passive-on" MR dampers, respectively. Using the innovative control algorithm for active and semiactive control of mass-distributed dynamic systems, e.g. stay cables proposed by ourselves, the vibration control of stay cable with semiactive MR damper is investigated.

The model stay cable experimental results indicate that the semiactive MR dampers can achieved much better control efficacy and provide a more significantly superior supplemental damping for a cable than both "Passive-off" and "Passive-on" MR dampers and the reason can be attributed to the pseudo-negative stiffness generated by semiactive MR dampers.

6174-26, Session 6

DSP-based electromechanical (E/M) impedance analyzer for active structural health monitoring

B. Xu, V. Giurgiutiu, Univ. of South Carolina

The electromechanical (E/M) impedance method is a powerful technique in active structural health monitoring (SHM). E/M impedance method utilizes as its main apparatus an impedance analyzer that reads the in-situ E/M impedance of piezoelectric wafer active sensors (PWAS) attached to the monitored structure. Present-day impedance analyzer equipments (e.g.HP4194) are bulky, heavy and expensive laboratory equipment that cannot be carried into the field for on-site structural health monitoring.

In this paper we present the implementation of a miniaturized DSP-based imped-

ance analyzer for active SHM. Two pieces of off-the-shelf low-cost hardware, a DSP board and an A/D-D/A converter board, are employed in this miniaturized impedance analyzer. The whole system consists of three main function modules: (1) excitation signal generation module; (2) data processing module; (3) data display module. Conventional impedance analyzers always use sine waves at a number of different frequencies as their excitation signals. For example, to produce an impedance spectrum with 401 points, 401 excitation signals have to be generated, sampled and analyzed. This is not time efficient. To address this issue, digitally synthesized signal sources which are abundant in frequency components are being investigated. For the data processing module, the performances of several data processing methods such as Discrete Fourier Transform, sine correlation, and chirp Z transform for impedance spectrum measurement are evaluated and compared in DSP real-time system. In the same time, the possibility of using low sampling frequency and low-cost A/D card is explored by using time-equivalent sampling technique for recording repetitive signals. The damage data display module is being developed by the use of the damage index approach, which provides a direct representation of the health status of structure being monitored. Two damage index methods, the root mean square deviation and the correlation coefficient deviation, are used.

A proof of concept of this miniaturized impedance analyzer has been constructed and tested experimentally; preliminary results are being presented. Finally, we present a discussion of the possibility of using the same hardware configuration for other active SHM techniques, such as the pitch-catch and pulse-echo wave propagation methods.

6174-27, Session 6

Towards autonomous sensing

D. J. Inman, B. L. Grisso, Virginia Polytechnic Institute and State Univ.

For some time the smart materials and structures community has focused on transducer effects and the closest advance into actually having the “structure” show signs of intelligence is to include adaptive control implemented with a smart structure. Here we examine taking this a step further by attempting to combine embedded computing into a smart structure system. The system of focus here is based on an integrated structural health monitoring on a panel in this case that consists of a completely wireless, active sensing systems with embedded electronics. Structural health monitoring is receiving increased attention in industrial sectors and in government regulatory agencies as a method of reducing maintenance costs and preventing disasters. One technical roadblock to implementing this technology is the miles of wiring involved in monitoring a large system such as a bridge, airplane or building. Here we propose and discuss an integrated autonomous sensor “patch” that contains the following key elements

- Power harvesting from ambient vibration and temperature
- Battery charging circuit
- Local computing and memory
- Active sensors
- Wireless transmission

These elements should be autonomous, self contained and unobtrusive compared to the system being monitored. Each of these elements is discussed as a part of an integrated system to be used in structural health monitoring applications.

6174-28, Session 6

Sensing schemes for state estimation in turbulent flows and flexible structures

M. Krstic, Univ. of California/San Diego

Turbulent fluid flows and flexible structures are governed by partial differential equation models. Few of their many “states” are measurable and it is typically those on the boundaries of their domains, such as for example the pressure at the walls of the fluid flow domains or the tip displacement on a flexible beam. Several choices exist in selecting sensors for esimating the entire dynamic fields of these systems based on their boundary measuments. Informed choices of sensors can be made only if one understands whether state estimation is feasible with such sensors. We have developed a methodology for designing state estimators in distributed parameter systems which allows state estimation to be achieved with the simplest possible sensing architectures. The spatially dependent gain functions of our state estimators are derived in closed form and also depend explicitlly on system parameters, eliminating the need for intense numerical computations typical for systems modeled by partial differential equations. Future applications of this methodology include turbulence estimation problems in weather forecasting and beam vibration estimation in atomic force microscopy.

6174-29, Session 7

Wireless and distributed sensing of the shape of morphing structures

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Monitoring the shape of morphing is essential for their effective and safe operation. However, current sensing systems such as fiber optic sensors are expensive, rigid, and unsuitable for monitoring large shape changes without being susceptible to failure or performance degradation. Therefore, a new class of sensors that does not suffer from these serious limitations is presented. The proposed sensor system relies in its operation on a specially configured distributed network of wires that are embedded in the composite fabric of these structures. The output of the sensor network is wirelessly transmitted to a control processor to compute the linear and angular deflections, the shape, and maps of the strain distribution and power flow over the entire surface of the morphing. The deflection and shape information are vital to ascertain that the structure is properly deployed and that its surfaces are operating wrinkle-free. The strain map ensures that the structure is not loaded excessively to adversely affect its service life. While the power flow map provides a metric that uniquely identifies the structural health in a manner that mimics biological systems which tend to redistribute the load and redirect its path away from the injured sites.

The equations governing the operation of the sensor network are developed for a beam-like morphing structure using the non-linear theory of finite elements. The resulting equations will provide the sensor with its unique interpolation capabilities that make it possible to map the linear and angular deflection and strain fields as well as the power flow distribution over the entire surface of the morphing structure. The theoretical and experimental characteristics of the sensor network are determined in both the time and frequency domains under static and dynamic loading conditions. The results obtained are used to demonstrate the merits and potential of this new class of sensors as a viable means for monitoring the static and dynamic deflections of 1-D morphing structures.

Integration of the proposed sensor network with the supporting electronics and with arrays of flexible actuators will enable the development of a self-contained, actively controlled, and autonomously operating new generation of morphing.

6174-30, Session 7

Piezoelectric-base energy-harvesting power sources for gun-fired munitions

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This paper presents a new class of piezoelectric based energy harvesting power sources for use in gun-fired munitions or other similar applications requiring high G survivability (3 U. S. Patents pending). These power sources are designed to harvest energy from the firing accelerations as well as vibratory motion and spinning of munitions during their flight and convert it to electrical energy that could be used directly by power consuming electronics onboard munitions or stored. The developed piezoelectric based energy harvesting power sources are shown to produce enough electrical energy for many munitions applications. The power sources are designed to withstand firing accelerations in excess of 100,000 G. The power sources have been shown to have the potential of completely eliminating the need for chemical batteries in many fuzing applications, while having the added advantage of providing for considerably more safety since with such power sources, fuzing electronics are powered only after the munitions have exited the barrel and have traveled for certain amount of time. Prototypes of a number of designs of this class of energy harvesting power sources for various power requirements have been constructed and successfully tested in the laboratory using a specially designed and constructed drop-testing machines and by the U. S. Army (ARDEC) using air guns.

6174-31, Session 7

Low-cost wireless corrosion and conductivity sensors

M. M. Andringa, J. Puryear, D. P. Neikirk, S. L. Wood, The Univ. of Texas at Austin

Our society depends heavily on an infrastructure of buildings, bridges, roadways and other such structures. The long design lives of these structures coupled with the inaccessible nature of particular areas of interest create unique challenges when designing monitoring systems. Previous efforts at The University of Texas at Austin have led to the development of a prototype embeddable sensor to detect the onset of corrosion in steel reinforced concrete using non-invasive techniques.

Unlike many sensors either on the market or under development elsewhere, these

sensors are designed to be extremely simple and low cost. The sensors are embedded in the concrete and are powered and interrogated through the use of inductively coupled magnetic fields. Without the need for batteries, the sensors can conceivably last the lifetime of the structures which they are designed to monitor.

The sensor was originally designed to trigger a shift in resonant frequency due to crossing a corrosion threshold; however, tests in concrete revealed that as the sensing wire corrodes, it behaves more like a changing resistance than a switch due to the conductive environment of the surrounding concrete. An improved sensor and data analysis technique takes into account both the resonant frequency and the width of the sensor resonance and combines them into a single value, pseudoQ. Initial tests of the redesigned sensor used varying concentrations of salt water to simulate a conductive environment and show that despite small changes in pseudoQ due to increasing conductivity, there is a clear distinction between a broken (or corroded) and intact wire.

Although the corrosion sensor measurements are interpreted using a simple threshold level, the sensing mechanism could be applied to a continuous range of values. Recent computer simulations suggest that the same overall sensor technology coupled with a modified sensor circuit could be used as an unpowered wireless conductivity monitor. Such measurements may allow the early detection of corrosive environments without the need for corrosion to have already occurred. By combining such a conductivity sensor with the corrosion sensor already under development, it may be possible to obtain an even better understanding of the current state of monitored concrete structures, thus allowing more informed decisions on appropriate maintenance needs.

6174-32, Session 7

Miniaturized wireless smart sensor with active sensing for structural health monitoring

L. Liu, F. Yuan, North Carolina State Univ.

Wireless smart sensor has been continuously investigated for structural health monitoring (SHM) recently. With embedded processor and wireless communications capabilities, networked sensor nodes can not only acquire information from environmental source, but also exchange the information among nodes and assess all information locally. As a low cost alternative for wired sensor systems, wireless smart sensor networks hold the promise in that they have the potential to improve damage detection strategies and SHM systems.

Quiet a few prototypes of wireless smart sensor have been developed and demonstrated these years. Almost all of them have identical system architecture, and only differ from the choices of components which mainly include various transducers, signal condition circuit, analog-to-digital converter, microprocessor and radio frequency chip. Systems with active sensing functionality which can actively excite waves as signal carrier are not available. Although several researchers have addressed this issue and proposed ideas for the active sensing, those work were based on bread board experiment and not optimized for practical applications as low power limitation is enforced. There are great challenges to implement actuation capability in wireless sensors when many factors and requirements, such as physical volume, speed, accuracy and power consumption are involved.

A miniaturized prototype of wireless smart sensor to integrate wireless communication, distributed computation capability with low power consumption into a small volume unit has been developed by North Carolina State University. Each unit provides mega-Hz level sensing functionality and hardware associated computation capability by the support of FPGA. With flexible design, the prototype can accommodate various needs by replacing the sensor layer which has a unique interface to other layers.

In this paper, the design of a novel wireless sensor group with active sensing capability is proposed for SHM applications. A dedicated actuation board complying with the interface of our sensor platform is developed to drive piezoelectric to excite ultrasonic stress wave. With pulse width modulation (PWM) and FPGA involved, the implementation of low power amplifier for piezoelectric in wireless smart sensor is investigated and discussed. A sensor group with active sensing is proposed by using a sensor node with the actuation board, called master sensor, and several other nodes with sensor boards, called slave sensors. Experiment on the proposed sensor group is introduced and discussed.

6174-33, Session 7

Thick film wireless and powerless strain sensor

Y. Jia, Univ. de Puerto Rico Mayagüez

This paper presents a prototyping of thick film wireless and powerless strain sensor, which consists of a planar inductor-capacitor (L-C) resonant circuit on DuPont Kapton(r) thick film. L-C resonant circuit is employed, in which, the capacitance changes with changes to applied strain, and an inductor L acting as the power receiving and signal transmitting part. Physic principle and the design parameters of the sensor are discussed, and the sensors with specific specification are demonstrated. The experimental validations were performed and preliminary results are demonstrated.

6174-34, Session 8

Sensor placement optimization in structural health monitoring using genetic and evolutionary algorithms

H. Gao, J. L. Rose, The Pennsylvania State Univ.

Structural Health Monitoring (SHM) is of major concern in civil, mechanical, and aerospace (CMA) systems in order to provide early warning of structural degradation and damage and to prevent catastrophic failure. Currently, a suite of SHM technologies are under development including for example vibration based methods, ultrasonic guided wave based methods, electro mechanical (E/M) impedance based methods, and fiber optics based methods. Ultrasonic guided wave based technologies are commonly used in nondestructive evaluation (NDE). Guided wave based methods have the merits of long distance monitoring potential, easy accessibility for in service structural components, and wireless interrogation potential, indented for damage monitoring in a median scale structural area. Focusing on smaller structural damage and structural degradation, E/M impedance based methods are intended to be used in local damage monitoring and detection.

Current research works in ultrasonic guided wave and E/M impedance based SHM are mostly focused on damage monitoring mechanics, signal processing, and decision-making technologies. Sensor placement is for the convenience and quality of damage detection and signal processing. However, moving from laboratory research to real application, application requirements are critical when considered quantitatively in sensor placement strategy, since they directly relate monitoring system cost to the infrastructure safety.

In this paper, health monitoring of an aging aircraft wing is considered. A damage detection probability model is developed to evaluate the performance of SHM sensor networks. Ultrasonic guided wave sensors are used to monitor millimeter scale crack and corrosion damages. In this scale, the damage distribution is modeled to have larger probability along the rivet lines and stiffening ribs. Constraints on sensor location are also prescribed at the inaccessible regions on the wing section. E/M impedance sensors are used to monitor a local region of a wing panel section. A refined damage distribution map is modeled to resolve sub millimeter scale damages in the structure. The performance of each individual sensor is modeled with a sensor coverage function. The performance of the entire sensor network is then considered as the collaborative performance of all of the sensors in the network.

Genetic and evolutionary algorithms (GEA) are used to optimize the sensor placement decision process. Genetic and evolutionary algorithms are newly developed optimization methods by mimicking the process of natural selection and evolution. These methods are particularly capable of solving non-linear, complex, and non-differentiable problems. In particular, Covariance Matrix Adaptation Evolutionary Strategy (CMA-ES) is used in this paper. Optimized distribution of ultrasonic guided wave and E/M impedance sensor networks for the sample problems are obtained. The trade-off between sensor number and sensor network coverage is also obtained, which reveals the quantitative relationship between the monitoring system cost and aircraft aviation safety.

6174-35, Session 8

Real-time determination of aerodynamic parameters using spatially distributed sensors

D. K. Pullen, J. E. Hubbard, Jr., A. B. Flatau, Univ. of Maryland/College Park

Spatially distributed sensors made of smart materials such as PVDF film have long been used as sensors to obtain pressure readings [1]. Shaping of the collection electrodes has been shown to enable distributed sensors to calculate center of pressure or force with minimal processing. Spatial weighting techniques are applied that generate modifications to the sensor electrode shapes and allow pressure readings to be obtained on curved surfaces such as wings without the use of pitot tubes and with minimal surface obstruction. Processing of these readings enables multiple aerodynamic properties of the airfoil to be determined in real-time.

Development of the spatial weighting requirements for the synthesis of lift and drag sensors will be presented. Additionally, aerodynamic properties of the airfoil will be used to allow calculation of the angle of attack of the relative wind.

A prototype distributed sensor was designed, fabricated and tested on a foam

core wing in a wind tunnel. Testing was performed on a NACA 23015 airfoil. The wing had a 12 inch span and a 3.5 inch chord. Wing rigidity was provided with one layer of 4.5 mil and one layer of 9.0 mil pre-impregnated fiberglass. Truth sensors in the form of calibrated pressure taps were used for data correlation. These sensors were installed by replacing the solid core with a channeled foam core to allow precise placement of the pressure taps. The wind tunnel test section is 12 inch by 12 inch and attained Reynolds numbers of 240,000. Angles of attack were varied from -10 to +15 degrees.

Theoretical pressure coefficient distributions were obtained using Femlab and DesignFoil and were validated with 40 mil pressure taps. Theoretical normal and axial pressure distributions were calculated using Matlab. The prototype sensors which obtain the lift and drag components of pressure were placed on both the top and bottom surfaces. Results from the shaped electrode sensors are compared with pressure distribution data obtained from theory and truth sensors.

[1] Pressure Distribution Characterization System: U.S. Patent Number 5,054,323; October 8, 1991.

6174-36, Session 8

Stretchable silicon sensor networks for structural health monitoring

K. Huang, P. Peumans, Stanford Univ.

In many applications, distributed networks of sensors with high temporal and spatial resolution are required to make informed decisions or enable a novel type of information to be gathered. We present a technique to realize very dense and cost-effective networks of high-performance sensors that can be deployed on the centimeter to meter-scale. The two-dimensional network is entirely processed in a CMOS foundry before it is “stretched” to the target size and “cut” to the right shape. Our technique therefore combines the maturity of CMOS fabrication techniques with the ability to quickly assemble a fully interconnected 2D sensor network of arbitrary size and shape. Furthermore, the sensor networks are rugged because no wire bonds or solder connections are needed and can be seamlessly integrated into structural materials.

To realize dense sensor networks for SHM in a cost-effective way, we have developed stretchable two-dimensional (2D) sensor networks that are based on foundry-processed silicon wafers. Each of the sensor network nodes can house a small (~50-200*m diameter), high-performance silicon integrated circuit (IC) with sensor, sensor interface, local processor, and a network interface. The stretching ability of the network is achieved by realizing the network and power connections as standard CMOS interconnects on narrow silicon ridges configured as springs. All deformation takes place in the spring-like interconnects, minimizing the maximum strain. Starting with an 8" silicon wafer, and assuming 1*m-wide interconnect ridges, a very large 2D network of ~106 sensors can be manufactured on a single wafer that can subsequently be stretched to a diameter of ~10 meters. The crystalline silicon substrate, metal interconnects and dielectric layers can sustain strain levels of 1%. Previous work has indicated that crystalline silicon can sustain maximum strains of 2% before failing. The maximum size and sensor density can be traded off against each other. As the fabrication process improves, the sensor node count and stretching capacity will both increase.

The 2D sensor networks are damage tolerant (insensitive to failure of interconnects), scalable (networks with 100 to ~107 nodes can be fabricated), reconfigurable (by virtue of embedded logic) and durable (by embedding into composite panels or protective films). Despite being based on CMOS technology, our proposed technology is cost-effective. Currently, the cost of processing an 8" silicon wafer is approximately $1,000 or $30,000/m2 (in volume). By stretching the network to a 1000 times its original area, the cost of the proposed sensor network is effectively $30/m2. At this price point, the integration of the proposed networks into civil and military structures for SHM, and into medical diagnostic and therapeutic equipment, becomes attractive. If the integration density of electronic functions within the nodes is not critical, the cost can be further reduced by the use of older process technologies.

6174-37, Session 8

Discrimination of internal wall thinning in pipeline by distributed optical fiber sensor

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ABSTRACT: The monitor of pipeline integrity and disturbance is very important in many industries, Pipeline’s disturbances, especially corrosion that is responsible for most failures of pipeline, may lead to serious operational problems, but generally not monitor because lack of reliable and durable test techniques. Although UT diagnostic widely used today, inspections for pipeline in such systems are enormously time consuming and expensive. We attempt to find a new diagnostic method by attaching the BOTDA optical fiber sensor spirally on the outer surface of pipeline to solve it. If thinning occurs, the deformation caused by inner pressure will reflect the thinning information, which means a special strain distribution along the optical fiber occurred, by numerical simulation and extracting of strain distribution along optical fiber, the special characteristic of distributed strain data can be used to determine the location and shape (depth and size) of the corrosion-induced thinning. Since distributed optical fiber measurement can cover large range, and needn’t local power supply, based on this distributed test technique, it is possible to found a SHM system of pipeline, it will become a safe, efficient and economy solution for monitoring corrosion/thinning of pipeline.

6174-38, Session 8

An electronic prosthesis mimicking the dynamic vestibular function

A. M. Shkel, Univ. of California/Irvine

This paper presents a functional architecture, system level design, and preliminary experimental evaluation of a unilateral vestibular prosthesis. The sensing element of the prosthesis is a custom designed one-axis MEMS gyroscope. Similarly to the natural semicircular canal, the microscopic gyroscope senses angular motion of the head and generates voltages proportional to the corresponding angular velocity.

Then, voltages are sent to the pulse generating unit where angular motion is translated into voltage pulses. The voltage pulses are converted into current pulses and are delivered through specially designed electrodes, conditioned to stimulate the corresponding vestibular nerve branch. Our preliminary experimental evaluations of the prosthesis on a rate table indicate that the device’s output matches the average firing rate of vestibular neurons to those in animal models reported in the squirrel monkey and the guinea pig animal model experiments. The proposed design is scalable; the sensing unit, pulse generator, and the current source can be potentially implemented on a single chip using integrated MEMS technology.

6174-39, Session 9

Structural health monitoring using advanced Lamb wave techniques

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The development of structural health monitoring techniques may offer significant benefits relating to the safety, maintainability, and reliability of civil, mechanical, and aerospace systems. Structural health monitoring, or SHM, refers to automated methods for determining the integrity of such systems. Many SHM techniques are based on traveling or standing waves, with the assumption that any damage to a structure will result in changes to the mass, stiffness, or damping which will affect the dynamic behavior. For highly localized damage, such as cracking, the use of elastic wave techniques has been considered. In particular, the use of Lamb waves - guided waves that occur in a free plate - has been explored for detecting damage in plate and shell structures. This paper presents a brief overview on the use of piezoelectric sensors to create Lamb waves suitable for damage detection, along with detailed descriptions of some advanced Lamb wave techniques currently under investigation. One focus area is on the detection of corrosion or wear damage which results in a decrease in thickness due to material loss. The effects of thickness loss on Lamb wave behavior have been investigated through the use of closed-form and analytical models, and through experimental testing. Attention also has been focused on the detection of delaminations and disbonds in composite materials. Lamb wave techniques offer a unique method to detect these types of damage, which might result due to impacts, yet may not be visible. Experimental and analytical results are presented to illustrate the use of such techniques. Lastly, beamforming techniques offer the potential to propagate Lamb waves over greater distances by concentrating the wave energy in specific directions as well as to more accurately determine damage locations by more precise control of the waves. Recent experimental and analytical results on beamforming techniques utilizing multiple piezoelectric transducers are presented.

6174-40, Session 9

Propagation of guided Lamb waves in bonded specimens using piezoelectric wafer active sensors

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The nondestructive evaluation (NDE) of adhesively bonded structure is a complex process. Earlier work has confirmed that ultrasonic waves are influenced by the properties of the material in which they travel. Acousto-ultrasonic methods have

been used by previous researchers to generate ultrasonic waves using coupled transducers. This paper will address the generation and propagation of ultrasonic guided waves (Lamb waves) using permanently attached piezoelectric wafer active sensors (PWAS). The time harmonic propagation in an adhesively bonded joint specimen consisting of two aluminum plates is studied. First the propagation of Lamb waves in a single aluminum plate is presented and then the effects of the linearly viscoelastic layer of the adhesive are considered. To determine the transfer function of the bond a lap-joint specimen is used. The natural frequencies of the joint are also calculated. The propagation features such as mode shapes, attenuation of the signals, and the dispersion of the Lamb waves in the adhesive layer are presented.

6174-41, Session 9

Passive network of Fabry-Perot-based sensors with optical multiplexing capabilities

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We introduce a technology for robust and low maintenance sensor networks capable of detecting micro-g accelerations in a wide frequency bandwidth (above 1,000 Hz). Sensor networks with such performance are critical for navigation, seismology, acoustic sensing, and for the health monitoring of civil structures. The approach is based on the fabrication of an array of highly sensitive accelerometers, each utilizing a Fabry-Perot cavity with wavelength-dependent reflectivity that allows for embedded optical detection and serialization. A unique feature of this approach is that no local power source is required for each individual sensor. Instead one global light source is used, providing an optical input signal which propagates through an optical fiber network from sensor to sensor. The information from each sensor is embedded into the transmitted light as an intrinsic wavelength division multiplexed signal. This optical rainbow of data is then assessed, providing real-time sensing information from each sensor node in the network.

This paper introduces a Fabry-Perot based accelerometer and examines its critical features, including effects of imperfections and resolution estimates. Mechanical-thermal and electronic noise estimates place the resolution of these sensors on the order of a micro-g. It is noted that nanometer level tolerance control of the physical structure is needed to maintain such resolutions during sensing. The paper then presents serialization techniques for the creation of a system of arrayed sensors and examines the effects of serialization on sensor response. It is demonstrated that simple linear serialization is possible for low optical order devices, provided specifically engineered distributed Bragg reflector structures can be constructed.

A combination bulk-micromachining and micromolding fabrication process is presented and is used to create the critical inertial sensing elements of the device. The expected high sensitivity and wide bandwidth of the device is enabled by a through-wafer bulk process that allows for the use of a large mass, defined in the bulk wafer, as the inertial sense element in conjunction with a low modulus suspension structure. This process also enables reflector structures by providing a highly polished wafer with a stable optical surface. For such wafers, an upper limit of 5% insertion loss is expected for each device, based on the observed free-space transmission losses through the individual components. In addition, this unique process allows for the formation of composite structures aligned in-situ to the geometry of the device. These composites passively control the dynamic response of the device's sense element, increasing sensor robustness while retaining high sensitivity by maintaining a near ideal deformable optical cavity behavior under variable loads and conditions. Over a thousand-fold reduction in the sensitivity of the device to cross-axis effects is estimated through the use of such composites in isotropic materials. A manual alignment stage, which has been developed to allow for the creation of a high precision Fabry-Perot cavity from discrete components to the required nanometer tolerances, is introduced. The described processes are used to create preliminary devices, which are characterized as accelerometers under small inertial loads (±25mg), with a resolution of 150mV/g.

6174-42, Session 9

Health monitoring of bonded composite repairs using fibre optic sensors

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Bonded composite patches are often used as an economical repair strategy to restore the strength of heavily loaded aerospace structures after impact damage or fatigue cracking. This may be in the form of scarf repairs in the case where there is a requirement for a flush surface, or external doubler repairs when the surface condition is not critical. However, the integrity of such repairs, particularly at the bonding surfaces, may degrade over time due to combined loading and environmental effects. This necessitates a highly conservative design paradigm to ensure adequate safety capacity. The incorporation of structural health monitoring (SHM) systems in bonded composite repairs to detect, at an early stage, any degradation of the repair, may allow the use of less conservative designs and increase the confidence and industry acceptance of this repair strategy.

SHM may be implemented by monitoring the strain in the vicinity of the repair and that at a far-field location in order to detect any load shedding from the repair which may be indicative of failure. This may be achieved by using fibre optic Bragg grating sensors. This paper will discuss the implementation of two such systems in typical bonded composite repairs based on finite element modelling and experimental investigations. One technique examined involves interrogating the Bragg grating sensors using conventional spectral analysis to obtain the strain measurements. This allows the system strains to be quantitatively obtained for the determination of repair integrity. The second method utilises coupled Bragg gratings which convert differences in strain into an intensity measurement, greatly reducing the hardware requirements for sensor interrogation. The performance of these two techniques will be compared and a discussion of the relative merits of the two systems will be provided, including issues such as sensor installation, power requirements, data processing and analysis, and the sensitivity, reliability, durability and robustness of the sensors and the system.

6174-43, Session 9

LPFG-based optical fiber whitelight interferometric distance sensor

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Optical fiber sensors have been widely exploited for displacement measurement, temperature sensing, medical diagnosis, and confocal microscopy, due to their compact size, light weight, remote operation, capability to operate in harsh environment, and immunity to electro-magnetic interference. Among different measurement schemes, distance measurement is one of the most common and widely applied techniques that often serve as the basis for the sensing of other physical parameters such as pressure, strain, vibration, and acceleration. Optical fiber whitelight interferometers for distance measurement have attracted a lot of attentions recently because they offer ultrahigh accuracy, large dynamic range, and robustness. We will present the development of an in-fiber whitelight Michelson interferometer using long period fiber grating for absolute distance measurement. The distance sensor system consists of a broadband light source, an optical circulator, a probe, and an Optical Spectrum Analyzer (OSA). The probe is made of a single mode fiber with a LPFG located at a distance from the cleaved fiber end, whose cladding region is covered by a mirror. A light generated by the broadband source propagates along the optical fiber core and is routed towards the LPFG by an optical circulator. When propagating through the LPFG section of the probe, one part of the wave continues to travel along the fiber core toward the sample under test while the other part of the wave is coupled into the cladding and starts to propagate along the cladding until it reaches the mirrored end of the probe. Reflected from the mirror, this cladding mode will trace its path back to the LPFG. Because of the reciprocity principle of light propagation, the reflected wave will be coupled back to the core mode. The part of the light that travels through the fiber core exits the probe, then is reflected by the sample, and finally is coupled back to the fiber core, thus interfering with the wave reflected from the mirror. The fringe pattern that results from these two interfering optical waves is routed to the OSA by the optical circulator, from which the absolute distance between the fiber probe and the sample can be determined. Fabrication of the sensor probe as well as the development of an efficient signal processing technique for fringe pattern interrogation will be presented. The advantages of the proposed distance sensor include ultra-precise absolute distance measurement, large dynamic range, simultaneous distance and temperature measurement, and self-calibrated high-speed data interrogation. We are interested in applying this novel distance sensor for near-field surface profiling of nanoscale structures and mechanical testing of MEMS thin film materials. In addition, it could have broad applications for damage detection of composite materials, real-time monitoring of manufacturing processes, and in-situ measurement of crack-tip plasticity.

6174-44, Session 9

Advanced nondestructive evaluation techniques for civil infra-structures using PZT patches

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Univ. (South Korea); D. J. Inman, Virginia Polytechnic Institute and State Univ.

This paper presents the results of experimental studies on piezoelectric lead-zirconate-titanate(PZT)-based nondestructive evaluation (NDE) techniques for civil infra-structures. PZT patches offer special opportunity for developing real-time in-situ health monitoring systems for large and complex structures, because they are small, light, cheap, and useful as built-in sensor systems. The impedance-based and the Lamb wave-based methods were applied to steel and reinforced concrete (RC) members, in this study. Several damage sensitive features were selected: i.e., root mean square deviation

(RMSD) of the impedance from the intact value, time of flight and wavelet coefficients of the Lamb waves. Sensor network systems composed of several PZT patches were used to detect the cracks inflicted at the welded zone of a steel member. The PZT patches were also used to detect multiple cracks in a RC beam under a 3rd point loading test. It has been found that the impedance-based method is effective to detect the cracks located near the PZT patches. Wavelet transform technique was applied for the time-frequency analysis of the measured Lamb waves, and their time of flights and wavelet coefficients were used as damage indicators. Support vector machine technique was successfully applied to the classification of several damage classes.

6174-45, Session 10

Condition monitoring of concrete structures using wireless sensor networks and MEMS

C. U. Grosse, Univ. of California/Berkeley and Univ. Stuttgart (Germany); S. D. Glaser, Univ. of California/Berkeley; M. Krueger, Univ. Stuttgart (Germany)

The inspection of building structures and especially of bridges is currently made by visual inspection. The few non-visual methodologies make use of wired sensor networks, which are relatively expensive, vulnerable to damage, and time consuming to install. Systems based on wireless sensor networks could be both cost efficient and easy to install, scalable and adjustable to different type of structures.

Acoustic emission techniques (AET) are an additional monitoring method to investigate the status of a bridge or some of its components. It has the potential to detect defects in terms of cracks occurring during the routine use of structures. Sensors with low price are essential for such monitoring systems to be accepted. However, AE recording and analysis technique needs powerful algorithms to handle and to reduce the immense amount of data. These algorithms are developed on the basis of neural network techniques and - regarding localization of defects - by array techniques. Although the development costs are relatively high of such a system, the target price for the monitoring systems will be several thousands Euro, depending on the size of the structure and the number of sensors necessary to cover the most important parts of the structure.

In this paper, the basic principles of a wireless monitoring system equipped with MEMS sensors is presented along with a first prototype. Micro-Electro-Mechanical-Systems and hybrid sensors form the heart of Motes (network nodes). The network combined multi-hop data transmission techniques with efficient data preprocessing in the nodes. Using this technique, monitoring of large structures in civil engineering becomes very efficient including the sensing of temperature, moisture, strain and other data continuously.

The authors work on details of network configuration, power consumption, data acquisition and data aggregation, signal analysis and data reduction and will present first results.

6174-46, Session 10

Ambient vibration study of Gi-Lu cable-stay bridge: application of wireless sensing units

K. Lu, Y. Chen, National Taiwan Univ. (Taiwan); J. P. Lynch, Univ. of Michigan; Y. Wang, Stanford Linear Accelerator Ctr.; P. Lin, Z. K. Lee, National Ctr. for Research on Earthquake Engineering (Taiwan); K. H. Law, Stanford Linear Accelerator Ctr.; C. Loh, National Taiwan Univ. (Taiwan)

Gi-Lu bridge was located at Nantou County, in the middle position of Taiwan. It is a modern designed pre-stressed concrete cable-stayed bridge, which crosses the Juosheui River in Taiwan. The bridge has a single pylon (58 meters height above the deck), two rows of harped cables (68 cables in total), and a streamline-shape single box girder. With 2.75 meters in depth and 24 meters in width, the box girder rigidly connects with the pylon and spans 120 meters to each side span. A total of 68 cables are installed in the bridge. The bridge was damaged during the Chi-Chi earthquake and it is now retrofitted and under operation. Several researches had been conducted in this bridge during the retrofitting stage which included the identification of cable vibration frequencies, traffic-induced vibration measurement. In order to develop the structural health monitoring system of the bridge, it is necessary to develop the reference data of the bridge and ambient vibration survey of the structural system is one of the important issues. Taking the advantage of the wireless sensing unit the ambient vibration system and the communication system (for longer distance) were modified to accommodate the wireless sensing system. Based on the measurement from the ambient vibration of the bridge the following techniques are used to identify the dynamic characteristics of the bridge:

1.Autoregressive method (Least Square),

2.Two-stage least-square method,

3.Stochastic subspace identification,

Comparison on the results of identification, including the system natural frequencies, damping ratios and mode shapes, from these methods is discussed. The results will be used as the reference information for the bridge monitoring.

6174-47, Session 10

Sensor failure detection using interaction matrix formulation

S. Nagarajaiah, Z. Li, Rice Univ.; M. Q. Phan, Dartmouth College

A novel sensor failure detection method is developed in this paper. Sensor failure considered in this paper can be any type of measurement error that is different from the true structural response. The sensors are divided into two groups, sensors that correctly measure the structural responses, are termed as reference sensors, and sensors that may fail to correctly measure the structural responses, are termed as uncertain sensors henceforth. A sensor error function is formulated to detect the instants of failure of the corresponding uncertain sensor, using the measurements from reference sensors and the uncertain sensor being monitored. The sensor error function is derived using the indirect and direct approaches. In the indirect approach, the error function is obtained from the state space model in combination with the inverse model and interaction matrix formulation. The input term is eliminated from the error function by applying inverse model and the interaction matrix is applied to eliminate the state from the error function. In the direct approach, the coefficient of the error function can be directly calculated from the healthy measurement data from the examined uncertain sensor and all reference sensors without having to know the state-space model of the system. Thus the need to know the state-space model of the plant can be bypassed. The sensor failure detection formulations are investigated numerically using a four degree-of-freedom spring-mass-damper system and experimentally using a 4m long NASA 8-bay truss structure. It is shown by means of numerical and experimental results that the developed sensor failure formulations correctly detect the instants of sensor failure and can be implemented in real structural systems for sensor failure detection.

Session organizer: Jerome P. Lynch and Jin-Song Pei, SSM09

6174-48, Session 11

A heuristic neural network initialization scheme

J. Pei, Univ. of Oklahoma

This paper introduces a heuristic methodology for designing multilayer feedforward network networks in modeling nonlinear restoring forces. It is well conceived that the way to decide an appropriate architecture to start neural network training has yet been established. This might be because this challenging issue can only be properly addressed by looking into the features of the function to be approximated and thus might be hard to tackle in a general sense. In this study, the author does not intend to provide an exhaustive solution to how to set up multilayer feedforward neural networks to approximate an arbitrary function, rather the focus is given to a significant domain function approximation problem of the force-state mapping to showcase the usefulness and efficiency of the proposed methodology. The governing physics and mathematics of nonlinear hysteretic dynamics and the strength of the sigmoidal basis function are exploited to answer the questions of how (in terms of neural network architecture, e.g., the number of hidden nodes in a universal approximator) and where (in terms of the initial values of weights and biases). Training examples are presented to demonstrate and validate the proposed initial design methodology. Comparisons are made between the proposed methodology and the widely used Nguyen-Widrow Initialization. Future work is also identified.

6174-49, Session 11

Multirate Kalman filtering for the data fusion of displacement and acceleration

A. W. Smyth, M. Wu, Columbia Univ.

Many damage detection and system identification approaches benefit from the

availability of both acceleration and displacement measurements. This is particularly true in the case of suspected nonlinear behavior and permanent deformations. In civil and mechanical structural modeling accelerometers are most often used, however displacement sensors, such as non-contact optical techniques as well as GPS-based methods for civil structures are becoming more common. It is suggested, where possible, to exploit the inherent redundancy in the sensor information and combine the collocated acceleration and displacement measurements in a manner which yields highly accurate motion data. This circumvents problematic integration of accelerometer data that causes low-frequency noise amplification, and potentially more problematic differentiation of displacement measurements which amplify high-frequency noise. Another common feature of displacement based sensing is that the high frequency resolution is limited, and often relatively low sampling rates are used. In contrast, accelerometers are often more accurate for higher frequencies and thus higher meaningful sampling rates are often available. The fusion of these two data types must therefore combine data sampled at different frequencies. A multi-rate Kalman filtering approach is proposed to solve this problem. In addition, a smoothing step is introduced to obtain improved accuracy in the displacement estimate when it is sampled at lower rates than the corresponding acceleration measurement. Through trials with simulated as well as experimentally recorded data the procedure's effectiveness is shown to be quite robust at a variety of noise levels and relative sample rates for this practical problem.

6174-50, Session 11

Application of outlier analysis for baseline-free damage diagnosis

H. Sohn, Carnegie Mellon Univ.; H. Park, Seoul National Univ. (South Korea); S. B. Kim, Carnegie Mellon Univ.

For the development of a robust online monitoring system for in-service structures, signal changes due to defects need to be distinguished from those caused by ambient operational and environmental variations of the structure in field. It has been reported that dynamic characteristics of an in-service structure could be influenced by ambient operational and environmental variation of the structure, and the ambient variation could often mask changes caused by damage. To address this issue, a data-driven damage detection technique, which does not rely on any past baseline signals, is proposed. First, a baseline-free feature sensitive to a defect is extracted based on a time reversal concept of modern acoustics. According to the time reversal concept, an input signal can be reconstructed at an excitation point if an output signal recorded at another point is reemitted to the original source point after being reversed in a time domain. However, this time reversibility of Lamb waves is violated when nonlinearity is caused by a defect along the wave propagation path. Examining the deviation of the reconstructed signal from the known initial input signal allows instantaneous identification of damage without requiring the baseline signal for comparison. Then, this study focuses on establishing the decision boundary for damage classification without relying on baseline data. An outlier analysis is adapted for this baseline-free establishment of the decision boundary for damage classification.

6174-51, Session 11

Damage tracking of base-isolated building using seismic response data

J. N. Yang, H. Huang, Univ. of California/Irvine

Base-isolated buildings and bridges have gained considerable popularity in recent years in seismic active areas, and the health monitoring of base isolators is of great concern. The ability to detect damages real-time on-line, based on vibration data measured from the structural health monitoring system, will ensure the reliability and safety of the structure. In particular, when a structure is subject to strong earthquakes, it is important to be able to determine the damage from the seismic response data either on-line or almost on-line. The problem is quite challenging when the restoring force of the base isolator is inelastic. The problem is further complicated by the fact that only a limited number of sensors can be installed in the structural health monitoring system, so that the seismic response data may not be available at all degrees of freedom of the structure and that the earthquake ground acceleration may not be measured.

In this paper, we propose a new data analysis method, referred to as the sequential nonlinear least-square estimation with unknown inputs and unknown outputs (SNLSE-UI & UO), for the real time on-line identification of structural damages. Several nonlinear restoring force models are explored for the base-isolation system, including the tri-linear hysteretic model and the Bou-Wen model. The effectiveness and accuracy of the proposed approach are demonstrated using a base-isolated building subject to various strong earthquakes. Simulation results demonstrate that the proposed approach is capable of tracking on-line the changes of structural parameters, such as the parameters of base isolators, leading to the identification of structural damages.

6174-52, Session 11

Damage detection in beams by roughness analysis

J. Wang, North Dakota State Univ.

Details of a new damage detection technique using roughness profile of structural mode shape are presented in this paper. To simulate a damaged beam numerically, a simplified solution of free vibration of a multi-cracked beam is obtained using general function. Numerical filter is used to extract roughness profile from the mode shape of the beam. The location of a crack in a beam is then determined by a sharp peak value appearing on the roughness profile. The size of the crack is also determined by the peak roughness value at the location of the crack. Specifically, two types of numerical filters, i.e., triangular and Gaussian, are examined. It has been found the former filter is more effective in damage detection than the latter one. Calculations show that a relatively low measurement resolution is required by the roughness-based method. Noise stress tests are also carried out to demonstrate the effectiveness and robustness of this method under the influence of noise. As verification, the proposed method is applied on the experimentally measured curvature mode shape to detect damage in a carbon/epoxy composite beam. The successful detection of crack in the composite beam demonstrates that the roughness-based method can be used efficiently and effectively in damage identification and health monitoring of beam-type structures.

6174-53, Session 11

Identification of structural damage using dynamic input-output measurements

R. Betti, H. Lus, G. Franco, Columbia Univ.

In this paper, two identification-based approaches for localizing and quantifying damage in a structure are presented. These approaches use dynamic measurements of the excitation and of the structural response and some information on the structural geometry to identify a reliable second order model of the system. By comparing the stiffness matrices for the undamaged and damaged configurations, it is possible to provide accurate estimates of the structural damage. The first algorithm starts from a first-order model of the system obtained through an ERA/OKID algorithm and transform such a model into a second-order model by using eigenvalues and eigenvectors of the associated complex eigenvalue problem. This approach provides very good identification but it requires that each degree-of-freedom has either a sensor or an actuator. When the instrumentation setup is not complete, this algorithm provides only a reduced-order model of the system and damage identification is not easily done. An expansion to a full-order model is done but only in some particular cases it leads to a successful damage identification. The second methodology is based on an evolutionary strategy. This methodology is not directly affected by the number of sensors/actuators and provides good damage identification even with an incomplete set of instrumentations.

6174-54, Session 12

Wireless corrosion sensors for reinforced concrete structures

N. P. Dickerson, M. M. Andringa, S. L. Wood, D. P. Neikirk, The Univ. of Texas at Austin

Corrosion of embedded reinforcing steel and the resulting deterioration of concrete structures is a worldwide problem. Structures exposed to marine environments or deicing salts are particularly at risk. Corrosion damage reduces the service life of a structural member and can create a serious safety hazard. Visual inspections are not effective in identifying the initiation and extent of corrosion that remains concealed until cracking and spalling occur. Traditional techniques for determining the presence, extent, and rate of corrosion are invasive and may be time consuming, expensive, and difficult to interpret. They are often employed only after corrosion damage is detected. Early detection of corrosion within reinforced concrete structures would give the owner the opportunity to remedy the situation before structural damage occurs.

The wireless corrosion monitoring sensors are under continuing development. The sensors provide a method of non-invasive and low cost early detection of corrosion in reinforced concrete. The embedded sensors are wirelessly powered by inductive coupling, and therefore, do not require batteries. Unlike traditional techniques that require an electrical connection to the reinforcing steel, the sensors use steel wires as sensing elements that are exposed to the same environmental

conditions as the embedded reinforcement. The behavior of these sensors has been extensively explored in wet and dry, hot and cold, chloride and non-chloride concrete environments.

The sensors detect corrosion thresholds and respond at a different characteristic frequency depending on the condition of the external steel sensing wire. Accelerated corrosion testing is underway to demonstrate the long-term viability of the sensors, and the results are being compared with traditional methods to detect corrosion, such as half-cell potentials and chloride ion levels.

6174-55, Session 12

Seismic vulnerability analysis of long-span cable-stayed bridges

C. Chang, D. Yan, The Hong Kong Univ. of Science and Technology (Hong Kong China)

Following the recent destructive events, bridge and highway infrastructure engineers face new challenges relating to the safety and the integrity of critical structures under seismic attack. A structure is defined as vulnerable if any small damage will trigger disproportionately large consequences or even lead to a cascade of failure events and progressive collapse. Vulnerability of a structure depends on factors including the properties and locations of damaged components as well as the way these components are connected to the rest of the structure. In this paper, a dynamic elastoplastic analysis is used for the vulnerability study of cable-stayed bridges under seismic excitation. Based on the material and geometrical properties, elastoplastic models for different components in the bridge are first established. Nonlinear dynamic analysis is then performed for the bridge to identify the failure mode initiated from damages of some bridge components. Assuming that the behaviors of damaged components can be modeled using plastic hinges, the stiffness degradation of the bridge under these damage conditions can be numerically quantified. This stiffness degradation can be used as an index to determine the vulnerability of the bridge. The proposed vulnerability analysis technique is illustrated on a cable-stayed bridge in China.

6174-56, Session 12

A novel real-time structural damage identification strategy with neural networks

B. Xu, Hunan Univ. (China) and Univ. of Missouri/Rolla; G. Chen, Univ. of Missouri/Rolla

Structural damage detection has become an increasingly important research topic for health monitoring, performance assessment and safety evaluation of existing infrastructures. Mathematical-model-based structural identification algorithms for civil engineering structures, which are applicable in concept to most structural models, have been proposed in the past two decades. Most of the widely used mathematical-model-based algorithms identify structural parameters using eigenvalues or mode shapes extracted from dynamic responses. All of the algorithms by the use of frequencies or mode shapes can only be applicable for linear systems. But structural systems can not be treated as linear system when damage occurs. Moreover, because it is difficult to determine the time instant of damage initiation, which induces frequencies and mode shapes changes, the frequencies and mode shapes extracted from the whole dynamic response history that includes the eigenvalues of both undamaged and damaged status of a structure usually can not present the actual damage scenario. Therefore, it is crucial to develop a real-time damage detection algorithm for structural monitoring system. The ability of artificial neural networks to approximate arbitrary continuous function and its parallel computation character provide an efficient soft computing strategy for real-time damage detection. In recent years, most structural identification strategies with neural networks have been proposed to give a qualitative indication of damage using dynamic response measurements or quantitative identification with eigenvalues or eigenvectors. The author developed a serial of identification methods for multi-degrees of freedom structures with the direct use of several seconds of forced or free vibration induced displacement, velocity measurements without any mode shapes and frequency extraction from the measurements. In this study, a neural-network-based real-time structural damage detection algorithm by the use of displacement and velocity measurements under earthquake excitation is proposed and examined by numerical simulations for a multi-degree-of-freedom object structure. The proposed algorithm can identify structural stiffness in a real-time manner. The performance of the proposed method for incomplete measurement and the influence of measure noise are also discussed. Since the strategy does not require the extraction of structural dynamic characteristics such as frequencies and mode shapes, it is shown computationally efficient, thus providing a possibly viable tool for real-time damage detection for health monitoring of civil infrastructures.

6174-57, Session 12

Damage detection of wooden buildings using chaos analysis and system identification

K. Hijikata, A. Mita, Keio Univ. (Japan)

As one of notable earthquakes across Japan, Hanshin-Awaji (Kobe) Earthquake occurred in 1995 struck an urban area for the first time. A lot of buildings in Kobe area suffered the extensive damage from the earthquake. Especially significant damage to the old wooden houses was evident. In contrast, there was a little damage to the recent houses employing the current building regulation.

Recently, structural health monitoring systems are getting strong attention for observing the earthquake-resistance of old houses. For the purpose of maintenance of aged houses, it is gradually recognized that the structural health monitoring systems are promising tools for reducing the maintenance costs effectively. For example, it is known that the chaos analysis method is effective as an earthquake-resistance evaluation method. This research was able to determine the physical parameters of the building that contribute to an earthquake-proof method of the chaos theory most. It could improve earthquake-resistance evaluation by using system ID and the chaos analysis methods.

6174-58, Session 12

Monitoring structural damage in complex connections

C. Mei, Univ. of Michigan Dearborn

A vibration-based monitoring process is proposed that adopts a different viewpoint than modal-based methods currently practiced. In addition to the usual modal characterization, vibration can also be described as traveling waves, which propagate in a continuous structure and are reflected and transmitted at a structural discontinuity. While modal responses depend on the global properties of the structure, the reflection and transmission characteristics depend only on the local properties of the structural damage. As a result, structural health monitoring based on wave vibration characteristics is more sensitive and reliable. In this paper, an L-shaped beam is considered as an example. The reflection and transmission characteristics of the structural joint with various severity of damage are studied both analytically and experimentally. The experimental study involves using sensors to measure structural vibrations and extracting joint damage related information from the quantified reflection and transmission characteristics.

6174-59, Session 13

Monitoring smart concrete beams in flexure using polymeric-based composite sensors

Y. Choi, Kyungpook National Univ. (South Korea)

Concrete may the economical material available for buildings and civil structures due to various important its properties such as high compressive strength, wear resistance, abrasion resistance and durability. The most disadvantages of concrete structural elements are its cracks in flexure. Visual inspection is difficult and provides little detailed information in crack defects. Recently, a new trend, called smart concrete or structure, has been emerged using sensor technology for monitoring cracks or defects of concrete structures.

A method designed to monitor or characterize the cracks in concrete beams in flexure using polymer-based composite sensors is conducted in the present work. The embedded polymer-based composite sensor shows a potential to evaluate the conditions of concrete beams in flexure such as the time of initial crack, electrical resistance versus load and crack width curves using data acquisition system.

6174-60, Session 13

Health monitoring method for plate structures using continuous sensors and neural network analysis

J. W. Lee, Korea Institute of Machinery and Materials (South Korea); G. R. Kirikera, I. Kang, M. J. Schulz, V. N. Shanov, Univ. of Cincinnati

A method for impact and damage detection on a plate using strain responses from long continuous sensors and analysis by a neural network technique was presented and verified by numerical simulation. The response characteristics of continuous sensors, which are long ribbon-like sensors, were studied by simulation of wave propagation in a panel. The advantage of the continuous sensor is to improve damage detection by having a large coverage of sensors on the structure using a small number of channels of data acquisition. Strain responses from the

continuous sensors were used to estimate the damage location using the neural network technique. Several numerical wave propagation simulation runs for a plate were carried out to train the neural network and verify the proposed method for damage localization. Some different training methods were used and compared. The identified damage locations agreed reasonably well with the exact damage locations. Overall, the approach presented is meant to simplify the instrumentation needed for damage detection by using continuous sensors, a small number of channels of data acquisition, and training a neural network to do the work of locating the damage source.

6174-61, Session 13

Active chaotic excitation for bolted joint monitoring

T. Fasel, M. D. Todd, Univ. of California/San Diego; G. Park, C. R. Farrar, Los Alamos National Lab.

Recent research has shown that high frequency chaotic excitation (AM chaos) and state space reconstruction may be used to identify incipient damage (loss of preload) in a bolted joint. In this study, a new experiment is undertaken with updated test equipment, including a piezostack actuator that allows for precise control of bolt preload. The excitation waveform is applied to a macro-fiber composite (MFC) patch that is bonded to the test structure and is sensed in an active manner using a second MFC patch. A novel prediction error algorithm, based on comparing filtered properties of the guided chaotic waves, is used to determine the damage state of a frame structure and is shown to be highly sensitive to small levels of bolt preload loss. The performance of the prediction error method is compared with several standard structural health monitoring damage features that are based on time series analysis such as autoregressive models.

6174-62, Session 13

Structural health monitoring of an existing 8-story building using strong motion observation data and structural design data

K. Morita, Building Research Institute (Japan); M. Teshigawara, Nagoya Univ. (Japan)

If we have to reduce life cycle costs of a building from construction to maintenance, it is very effective to monitor structural health of a building. Most buildings built during 1970's construction rush in Japan seem to rapidly deteriorate, and it is necessary to establish structural health estimation of these buildings. Many applications of health monitoring system to buildings and building structural models have been carried out, and structural damage and condition are fundamentally grasped only based on the measurements in most cases. Though good identification results are reported in the tests of building structural models in laboratory, it is difficult to identify damage in a real building because of lack of higher modes, shortage of number of sensors and increase in the error of parameter estimation. In this paper, a hybrid health monitoring system combined a sensing system with an analytical modeling system to help such lack and shortage will be proposed and results of identification will be mainly discussed. Target building is an 8-story steel encased reinforced concrete building which was constructed in 1998. In this structural health monitoring system, strong motion observation data is used and accelerometers were installed just after the completion of construction at 1st story, 2nd story, 5th story and 8th story. By use of system identification using ARX model, natural frequency, damping ratio and participation function are calculated, and abbreviated equivalent story stiffness can be also determined by using Moore and Penrose generalized inverse matrix. From the identification results, natural frequency and abbreviated equivalent story stiffness tend to decrease by the aging. Especially, just after the completion of construction and after a large earthquake, changes of natural frequency and abbreviated equivalent story stiffness are very remarkable. From the point of amplitude dependence, natural frequency and abbreviated equivalent story stiffness tend to change more by equivalent velocity of input energy than by peak ground acceleration. Analytical frame model is constructed from the structural design documents and abbreviated equivalent story load-displacement relationships are obtained by carrying out push-over analysis. By the comparison between analytical and identified abbreviated equivalent story stiffness, the structural health and conditions are estimated.

6174-63, Session 13

Database system for structural health monitoring of buildings

T. Inamura, A. Mita, Keio Univ. (Japan)

There is a growing necessity of structural health monitoring (SHM) systems that monitor the condition of buildings and infrastructures in order to promptly and quantitatively evaluate risks due to their deterioration or large earthquakes. An SHM system that can evaluate the safety and reliability of buildings and ensure the asset value is urgently needed. Various system identification methods and damage detection methods have been proposed and therefore the technology of SHM has been improved as a whole. However, in the course of developing such a system, it has been found that the establishment of a database that provides the statistical information of many structures.

Although many researchers have advocated the necessity for such a database for gathering building information, designers and contractors are kind of reluctant to reveal the information to third parties. In addition, it is not easy to set foot in the building which is private possessions. At the same time, it is also a fact that the purchasers, users or owners of buildings want to know easily the safety and reliability condition of buildings. Thus, there exist many stakeholders with respect to even one building.

The aim of this research is to develop a database which can obtain all stakeholders' consensus, that is, how to collect or store a lot of building data, how to analyze or identify the system using the data and how to provide the analysis results widely.

We use MATLAB Web Server as a Web application for release of system identification results, such as story stiffness and damping factor. These physical parameters as direct damage indexes of the structure are identified using complex modal properties obtained by numerical algorithm for subspace state space system identification (N4SID). N4SID is a method to estimate the state space representation based on multi-input/multi-output signals.

6174-64, Session 13

A video-assisted approach for structural health monitoring of highway bridges under normal traffic

Y. Chen, Univ. of California/Irvine; C. Tan, Wayne State Univ.; M. Q. Feng, Y. Fukuda, Univ. of California/Irvine

Structural condition assessment of highway bridges is traditionally performed by visual inspections or nondestructive evaluation techniques, which are either slow, unreliable or detects only local flaws. Instrumentation of bridges with accelerometers and other sensors, however, can provide real-time data useful for monitoring the global structural conditions of the bridges due to ambient and forced excitations. This paper reports a video-assisted approach for structural health monitoring of highway bridges, with results from field tests and subsequent offline parameter identification. The field tests were performed on a short-span instrumented bridge. Videos of vehicles passing by were captured, synchronized with data recordings from the accelerometers. For short-span highway bridges, vibration is predominantly due to traffic excitation. A physical model of a sequence of moving loads on an elastic structure is thus adopted in this study. Basic information of vehicle types, arrival times and speeds are extracted from the video images to develop a physics-based simulation model of the traffic excitation. This modeling approach aims at circumventing a difficulty in the system identification of bridge structural parameters. In current practice, system ID of bridge parameters is often based on the measured response (or system output) only, and knowledge of the input (traffic excitation) is either unknown or assumed, making it difficult to obtain an accurate assessment of the state of the bridge structures. The effectiveness and viability of this video-assisted approach are demonstrated by the results. Recursive Bayesian filtering is formulated to monitor the evolution of the state of the bridge with a vision of a real-time online structural health monitoring implementation. Issues related to object identification and recognition from the video images are also discussed.

6174-130, Poster Session

Modeling and simulation of magnetorheological fluids buffer for an elevator

H. Chen, G. Song, H. Gu, Univ. of Houston

Considering Magnetorheological Fluids(MR) damping coefficient is controllable,we apply the MR smart material to elevator buffer.This article presents the buffer's structure design, mathematic modeling and testing.The mathematic model is used to simulate the elevator MR buffer's dynamic properties and make sure the MR buffer have a more better properties then regular elevator buffer criteria.A real experiment is finished.It proves the MR buffer simulating model is reliable and can be use for elevator MR buffer's design and geometrical parameter optimizatiom.

Conference 6174: Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems

6174-132, Poster Session

Sensing behavior of magnetorheological elastomers

X. Wang, F. Gordaninejad, Y. Liu, M. Miller, Univ. of Nevada/Reno

Magnetorheological elastomers (MREs) are composite materials consist of magnetic particles that are aligned into chains or column-like structures which are embedded a polymer matrix. The structures of the magnetic particles within elastomers are very sensitive to the external stimulus of either mechanical force or magnetic field, which result in two phenomena: magnetorheoloy and magnetostriction. In this study we focus on investigating the sensing behavior of MREs through experimentally characterizing the dielectric properties of MREs. An experimental setup is developed to detect the changes of MRE dielectric properties subjected to external mechanical loads and applied magnetic fields. The relationship of the MRE's impedance and applied shear force is obtained. Several different MRE samples are prepared and tested with this experimental setup to compare their sensing capacities. A model is presented to explain the sensing mechanism of MREs.

6174-134, Poster Session

An automated structural damage-detection algorithm with implementation in wireless sensing units

Y. Lei, Xiamen Univ. (China)

A novel wireless monitoring system has been developed by researchers at Stanford University. It provides a low-cost and time saving data acquisition technology compared to the traditional wire-based sensing systems in health monitoring of structures in civil engineering. Moreover, with the inclusion of computational core in a wireless sensing unit, algorithms that automate the interrogation of measured data for indications of structural damage can also be locally executed. The investigation of effective damage diagnosis algorithms that can be embedded into the wireless sensing unit for the purpose of automated structural damage detection is the current research effort of the author.

The damage detection approach using time series analysis of vibration signals, which was proposed by Los Alamos National Laboratory (LANL) and later studied by the author, has shown great promise in the identification of structural damage. The algorithm mainly consists of a two-stage prediction model combing auto-regressive (AR) and auto-regressive with exogenous inputs (ARX). The residue error, which is the difference between the new measurement of the structure with unknown state condition and the prediction obtained from the AR-ARX model constructed from the reference signal of undamaged structure, is used as the damage-sensitive feature. The approach is very attractive for the development of an automated monitoring system because of its simplicity and its minimal interaction with users. However, there are still some problems in the approach. Time series analysis of a response data is not sensitive to minor structural damage and it cannot identify the location of structural damage. In addition, the extracted damage sensitive feature is influenced by the orders of the ARX model. Therefore, criteria for the selection of the ARX model should be investigated. In this paper, the earlier algorithm developed is further modified to increase the reliability of the damage prediction. For this purpose, the reference database is populated using an ensemble of normalized relative response of adjacent locations as opposed to the response at individual sensor location. The order of ARX model is determined from the stability plots of structural modal properties to distinguish the structural modes from any electric noise present in the data acquisition system. The modified algorithm is validated by applying it to detection of various damage patterns through the analysis of the numerical and experiment data of the benchmark building proposed by the ISAC-ASCE Task Group on Health Monitoring. The computational efficiency of the developed algorithm makes it particularly suitable to be implemented by the computational core of the wireless sensing units. As wireless sensing become increasingly less costly, a structure can be densely populated with such wireless sensing units, making it easier to localize s well as to identify structural damage.

6174-135, Poster Session

Field validation of a wireless sensor unit using self-anchored suspension bridge

G. Heo, Konyang Univ. (South Korea); W. Lee, Chungnam National Univ. (South Korea); G. Lee, Konyang Univ. (South Korea); J. Jeon, Chungnam National Univ. (South Korea); C. Kim, Hanyang C&A Corp. (South Korea)

This paper attempts to validate the effectiveness of wireless sensor unit by field experiments on a self-anchored suspension bridge. This wireless sensor unit was developed at Konyang University's SIS lab in Korea for real-time dynamic response measurement of structures. This sensing unit called SWMAS(Smart Wireless MEMS-based Sensor System) consists of a sensor system module, a control and processing module, and a wireless modem module. And it uses the power supply device that consists of sollar cell and recharge battery. In order to evaluate whether SWMAS would be applicable to structural monitoring system, an experiment was performed to a full-scaled structure, which was Yeongjong Grand Bridge, a self-anchored suspension bridge with a wire-based monitoring system placed inside. In the field experiments, the data from the ambient vibrations of the bridge were acquired in real-time using SWMAS. The experiments included an analysis of possible distance for wireless communication by the proposed system, and its reliability of power supply using solar cell and recharge battery. All data acquired so far were compared with those of wire-based monitoring system and with FE results. As a result, the comparison proved that SWMAS would be effectively applicable to smart monitoring system.

6174-136, Poster Session

Dynamic experiment and modeling of squeeze-mode smart damper for semi-active control of civil structures

G. Heo, Konyang Univ. (South Korea); G. Lee, J. Jeon, W. Lee, Chungnam National Univ. (South Korea); M. Choi, Korea Research Institute of Standards and Science (South Korea)

Magneto-rheological fluid is the fluid which is controllable with applied magnetic fields. This fluid is effective to semi-active control device in many areas. In this paper, a new MR technology is developed with squeeze mode damper. And various dynamic tests are performed to identify the dynamic characteristics of this device. This squeeze mode smart damper can be used permanently, and can be freely allocated at the sub-region of large structures such as buildings and civil engineering infrastructures. Also, a temperature effect in this device is improved by separating between the electromagnet and MR fluid. Various dynamic tests are carried out for a squeeze mode smart damper in many loading conditions, and force-displacement and force-velocity hysteresis loops are investigated for evaluation of its dynamic performance. In order to predict the dynamic performance of this device, three types of analytical models are compared with experimental results. Power model based on the damping and velocity, and Bingham model are adopted in the viewpoint of practical usage, and the Bouc-Wen model is adopted in analysis precision. These results verify that the developed smart damper is effective in semi-active control of civil structures.

6174-138, Poster Session

Studies on measurement of chloride ion concentration in concrete structures with long-period grating sensors

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The detection of chloride ion concentration is important in a variety of industrial applications, including pure, environmental, bio- and industrial chemistry. In particular, the salt damage of concrete structure due to the corrosion of reinforced bars in marine environment is normally caused by the penetration of chloride ion into concrete. Industrial health monitoring of chloride-ion distributions along different locations inside concrete structures in harsh saltwater environment is considered to be necessary for the maintenance and management of reinforced concrete structures.

Traditional methods of chloride-ion measurement involve titrations, colorimeters, fluorescence quenching, or ion-selective electrode. Most of the available sensors are based on an electrochemical reaction that has low sensitivity and is difficult to sense ions at low concentration levels. Recently, considerable attention has focused on long-period fiber gratings (LPGs) for a variety of applications owing to their low insertion losses, low back-reflection, and relatively simple fabrication. These gratings have offered wide applications for optical communication and sensing system such as in-fiber band rejection filters, and temperature, strain, or refractive index sensors. The LPG is extremely sensitive to the refractive index of the medium surrounding the cladding, thus allowing it to be used as an ambient index sensor with high stability and reliability. In this work, we will present the study of LPGs and their possible applications in chemical sensing for civil engineering.

The ability of the LPGs to detect changes in the surrounding refractive index or chemical solution concentrations has been studied. We have measured a concrete sample immersed in salt water solution with different concentration ranging from 0% to 25%. The results showed that the LPG exhibited a linear decrease in the insertion loss and resonance wavelength shift when the concentration increased. The error of salt concentration measurement is estimated to be ~2% and the limit of detection for chloride ion is about ~2ppm.

To enhance the sensitivity for chloride ion concentration, a chemical synthesis method was utilized to form gold nanospheres in water, and then coated those gold nanospheres on the grating surface of the LPG. The sensing mechanism is based on the sensitivity of localized surface plasmon resonance (LSPR) of self-assembled Au colloids (SAGC) on the grating portion of the LPG. The attenuated total reflection spectrum of SAGC is sensitive to the refractive index of its surrounding medium, which can be used for monitoring the solution bulk and for label-free detection of antigen/antibody binding or DNA at the surface of the Au colloids. Our results indicated that gold nanospheres modified on the fiber grating can increase its sensitivity in detecting solution concentrations significantly. Potential applications of this class of LPGs in environmental sensing (mainly for chemical solution concentrations) will be presented. The advantage of this type of the sensor is relatively simple of construction and ease of use. Moreover, the sensor has the potential capability for on-site, in vivo, and remote sensing, can be easily multiplexed to enable high-throughout screening of chemical reactions, and has the potential use for disposable sensors.

6174-139, Poster Session

Fiber-Bragg grating sensors for use in pavement structural strain-temperature monitoring

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In this paper, we describe the development and realization of a newly high-resolution temperature and strain sensor with fiber Bragg grating (FBG) technology. The proposed FBG sensor consists of a reference fiber grating and a grating pair scheme that could offer the potential of simultaneous measurement of strain and temperature for monitoring pavement structures. Experimental results showed that measurement errors of 6 microstrains and 0.13 degree C for strain and temperature could be achieved, respectively. Feasible applications of this sensor for monitoring pavement structures were investigated.

The reliability and long-term stability for temperature measurement with this type of sensor were examined by mounting the sensor on the surface of asphalt and concrete specimens, and several temperature cycles with a designed working temperature range up to 110 degree C were applied for at least 24 hours. An electronic thermocouple and a long-period optical fiber grating (LPG) sensor with similar function were also used to compare the performance. Small rms temperature variations (better than 1 degree C) and excellent long-term stability (within 2%) were obtained. The maximum variations in temperature for 48 hours were only 1.94% and 2.32% for asphalt and concrete specimens, respectively. Our results indicated that while the performance of this FBG sensor was comparable with that of the conventional thermocouple, its long-term stability was four times better than its counterpart, LPG sensor.

The feasibility of strain measurement for pavement structures was conducted by mounting this type of sensor on the surface of an asphalt specimen under the indirect tensile loading condition. The grating sensor was either bared or packaged. The strain coefficients of the bared and packaged grating sensors were measured to be 0.8 pm/ microstrain and 1.1 pm/microstrain, respectively. This difference was due to the constraints of polymer packaging. The measurement errors for bared and packaged sensors were found to be 9.7 microstrains and 8.6 microstrains, respectively. The packaged sensor was then used to perform the strain measurements on the surface of a Superpave gyratory compacted asphalt specimen. The static loading was applied on the loading strip vertically. One vertical and two horizontal dial gauges (accuracy of 0.01 mm) were used to monitor and ensure the relationship between loading and deformation is linear-elastic. The assumption of indirect tensile testing under plane stress condition was used to calculate strains at different locations and results were compared with the packaged sensor. The strain difference between the packaged sensor and theoretical predictions was about 30-40%. This was probably due to various factors including the surface treatment, adhesive skill, the appropriate assumption and the eccentric problem of dial gauges. Improvement of the theoretical models using numerical simulation is underway. This type of simple and low-cost fiber optic sensor is expected to benefit the developments and applications of pavement structures or transportation infrastructure. The FBG sensors will be embedded into specimens or field pavements to realize their robustness and effectiveness.

6174-140, Poster Session

A new sensor placement algorithm in structural health monitoring

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An initiative excitation-based sensor placement algorithm in structural health monitoring is presented. The algorithm aims for achieving the best identification of modal frequencies and mode shapes in structural health monitoring by selecting an optimum, or near-optimum sensor combination from a set of possible candidate sensor locations. This purpose is approached through estimation theory by considering the actual excitations and measured responses of a structure in question. The theory of the proposed algorithm is derived, and applied to the selection of sensor locations for dynamic testing of a cantilevered beam. Several other sensor combinations are also tested and the identification results are compared. It is shown that the algorithm appears to be a better alternative for sensor selection in structural health monitoring.. Furthermore, the different methodologies and the criterion for sensor placement are also examined in this paper.

6174-141, Poster Session

Material property sensing via magnetic resonance elastography

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Magnetic resonance elastography (MRE) is a technique to generate a spatially resolved map of the elasticity distribution in a material. Static or dynamic stresses are applied to a material resulting in displacements that are then imaged by various magnetic resonance imaging (MRI) techniques. Displacements correspond to strain within the image thus providing mechanical information about that material. MRI-derived displacements can be reconstructed into a 2D spatial map of the Young's modulus (measure of the stiffness of a given material). MRE has been successfully developed and implemented in clinical applications for in-vivo diagnostics of cancers,1,2 yet application of MRE towards material sensing has been largely ignored. MRE potentially allows 3D determination of elastic properties and mechanical losses.

In order to measure displacements, we have developed experimental apparati for quasi-static MRE and dynamic MRE. These employ MRI equipment and a mechanical compression device (motor) or a piezoelectric (to generate shear or compressive waves). We will show initial results on phantom samples, as well as filled elastomers that have been subject to aggressive aging. The extension of the method to samples in very small (microtesla) applied fields will also be demonstrated.

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6174-142, Poster Session

A novel edge sensor for web guiding

A. Seshadri, A. Abbaraju, P. R. Pagilla, Oklahoma State Univ.

Web handling refers to the physical mechanics related to the transport and control of web materials through processing machinery. Web guides are electro-mechanical or electro-hydraulic devices that are used to maintain the lateral position of the web on rollers. Control of web guides to maintain the lateral position of the web on the rollers prior to coating, printing, winding, and other web processes is critical for successful operation of a web process line. For example, large lateral movements of the web on rollers can cause slackness of the web, which can result in wrinkles. Hence, monitoring and tight control of the lateral position of the web is essential for increased productivity and manufacture of a quality finished web product.

Existing sensors, mostly infrared or ultrasonic, use the concept of 'blocking/unblocking' for web edge detection and measuring web lateral position. By measuring the amount of signal attenuation, due to blocking/unblocking, the edge position is inferred. The main drawback with this concept is improper or nonuniform signal attenuation due to web material variations and web opacity. Signal attenuation is not uniform for an infrared sensor if the opacity of the web varies. Similarly for nonwoven webs (spunbound), due to its uneven density and porosity, an infrared or an ultrasonic signal easily penetrates without any signal attenuation. Hence, accurate web edge sensing becomes difficult with these existing sensors.

To circumvent the limitations of existing sensing methods, the proposed sensing method for measuring web lateral position utilizes the phenomenon of light scattering from the web edge.

Collimated laser beam, inclined at an angle with the plane of web travel, is incident on the web edge and scattered light is collected by a linear array of equally

spaced fibers. The fiber array is spatially positioned such that it is perpendicular to the plane of the web and it does not receive the direct collimated laser beam. Based on the numerical aperture and core diameter of fibers, only a small conical beam of light is allowed to enter the fiber and hence with proper orientation, only one fiber receives the scattered light. When the web edge moves laterally, a different fiber receives the scattered light, and hence, the web lateral displacement is determined by finding the distance between the two illuminated fibers.

The free end of the fiber array is aligned on to a linear sensor array which consists of an array of pixels (photodiodes) having a constant pitch. Each fiber is aligned with a pixel of the sensor, and the pixels are continuously scanned. By comparing the voltage output of each pixel, the fiber illuminated by the scattered light is determined and hence the position of the web. Based on the position measurement and the scanning rate, the lateral velocity of the web can also be computed.

Various common limitations due to ambient light conditions, dust, high temperature environments, plane change issues, opacity of web and sensing a nonwoven web, are avoided by using the proposed sensing method. In this work, the sensing technique, construction of the sensing system, and experiments conducted to validate the proposed technique will be discussed.

6174-143, Poster Session

A new laser-based sensing system for monitoring and control of webs

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The term web is used to describe materials which are manufactured and processed in continuous, flexible strip form. Web materials cover a broad spectrum from extremely thin plastics to paper, textiles, metals, and composites. Products that involve web processing somewhere in their manufacturing include aircraft, appliances, bags, books, diapers, clothing, floor covering, newspapers, and many more. The quality of the finished products depends on monitoring and control of the process variables such as web transport velocity, lateral velocity, flutter (transverse velocity), and tension.

Web handling refers to the physical mechanics related to the transport and control of web materials through processing machinery. Design and control of web handling systems play an important role in successful manufacturing of the finished web. Currently, there does not exist a sensing system that can directly measure the key process variables such as web transport, lateral, and transverse (flutter) velocities. For example, the current practice is to infer the web transport velocity by measuring the roller angular velocity using a tachometer; it is done with the assumption that there is no web slip on the rollers. Web slip on rollers is unavoidable in most situations because of tension variations. Therefore, the current method of measuring web transport velocity is approximate at best. The goal of this paper is to describe a unique sensing system that can simultaneously and directly measure the key process variables.

Non-invasive laser doppler techniques have been employed to measure velocity of particles as well as solid objects. In this work, we will demonstrate a new optical sensing system based on reference beam laser doppler technique that is capable of measuring above mentioned key process variables of the web. Thus, providing a substantial amount of flexibility and accuracy in

monitoring and control of webs. In this approach, the laser light emitted from the laser diode is split into a reference beam and an illuminating beam. The illuminating beam is incident on the web edge. Due to Doppler effect, the light scattered by the web edge

has a frequency which is different from that of the illuminating beam. This frequency shift due to Doppler effect depends on the velocity of the web. The scattered beam is collected and heterodyned with the reference beam to determine the Doppler shift which in turn gives the measure of the web velocity. The doppler shift is uniquely determined by the wave length of the

illuminating light, the orientation of the viewing and illuminating directions with respect to the velocity components of the web. To heterodyne the scattered beam with the reference beam, it is necessary that the two beams be of the same polarization. One such optical setup which is capable of achieving this has been designed. The use of fibers in transmitting and receiving optics alleviate the alignment issues and provide flexibility to the sensing system.

In this paper, we will describe the principles behind the novel sensing system, its construction, and measurements to validate the proposed techniques.

6174-144, Poster Session

Workshop report: US-China workshop on the smart structures and smart systems

M. Tomizuka, Univ. of California/Berkeley

This workshop report is on the US-China Workshop on the Smart Structures and Smart Systems will be held in Jinan, the capital of Shandong Province, China on October 16-18, 2005. Specific subject areas covered by this workshop Integrated Sensing Systems, Mechatronics and Smart Structures Technologies. The objectives of the workshop are: (a) to evaluate the current status of research and education in the topic areas in the United States and China, (b) identify critical and strategic research and educational issues of mutual interest, (c) identify joint research projects and potential research teams for collaborative research activities, and (d) identify the research data, experimental test beds, and resources that can be shared by the researchers for joint research projects. Integrated sensing systems, mechatronics and smart structure technologies are utmost concerns of aerospace, civil and mechanical engineers for safety and reliability. These concerns are shared by the U.S. and China, and research and education at universities in the two countries must address these issues. Researchers and educators from the U. S. and those from China may collaborate for common goals and work together. Mechatronics refer to the synergistic integration of sensors, actuators, physical plants and computing devices for closed loop decision making. Synergy may be considered in terms of dealing with complexity, performance, overall cost of machinery, physical dimension, time for development, ease of installation, and so on. The mechatronic approach is essential in the development of industrial products such as robots and hard disk drives as well as in the design of smart structures and health monitoring systems for aerospace and civil infrastructures. This provides the motivation to organize the U.S.-China joint workshop with multidisciplinary representations from the aerospace, civil and mechanical engineering communities. About 10 leading educators and researchers in the field from the United States will attend the workshop and interact with those from China. The details of the workshop activities and outcomes will be reported in this poster presentation.

6174-145, Poster Session

Sensors: sensing rich design of drive trains for mechatronic systems

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This research develops mechatronic approaches to the design of drive trains for mechanical systems based on heavy sensing. A typical drive train includes an actuator (electrical motor), a set of gears, bearings and an inertia load (link), which may be connected to another drive train or an end effecter. The goal of this research is to emphasize sensors and sensing, and we answer to a question: What may be accomplished from the viewpoint of mechatroncis if we are rich in terms of sensing? The technical objectives of the research are 1) to study sensing of various signals in the drive train, in particular, those not utilized in conventional practice such as acceleration signals, force signal in the drive train and end effector's position, 2) to develop signal processing and decision making algorithms that take advantages of the sensed signals for betterment of performance and other mechatonic advantages, and 3) to demonstrate these benefits experimentally. New signal processing and decision making algorithms will handle nonlinearities and uncertainties in drive train mechanisms as well as the environment in which drive trains and entire mechanical systems operate. This will bring advantages to both producers and end users of mechanical systems, e.g. robots, assembly machines and other manufacturing equipment. The broader impacts will be from education, outreach and international collaboration. The project team includes the Principal Investigator, graduate student researchers and undergraduate researchers. Undergraduate students will be involved in this project through participation in experiments and mechatronics design.

6174-146, Poster Session

Novel sensors, actuators, and nanoskin based on carbon nanotube arrays

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Multi-wall carbon nanotube arrays mm in length were synthesized on Si wafers. Based on the long nanotube arrays, several prototype smart materials were developed including a biosensor, force actuator, and a nanoskin. The biosensor was formed by casting epoxy into the nanotube array and polishing the ends of the nanotubes. This electrode produced a near ideal sigmoidal cyclic voltammogram.

Electrochemical actuation of the as-grown nanotube array was demonstrated in a 2 M NaCl solution. The nanotube array force actuator is 1 mm square by 4 mm long and actuates up to 10 Hz. A driving voltage of 2 volts produces 0.15% strain. The nanotube array also can be used to develop biomimetic materials. The leaves of the Nelumbo nucifera (lotus) and Colocasia esculenta plants have large bumps which are covered with a highly hydrophobic wax. This hydrophobic material and surface roughness create a high wetting contact angle. Carbon nanotube arrays as-grown have demonstrated hydrophobic and capillarity properties that can mimic the hydrophobic mechanism found in these plants. The nanotube array has about twenty billion nanotubes per square centimeter of surface, and a high surface roughness. The high surface roughness can increase the hydrophobicity of an already hydrophobic surface resulting in a high contact angle. The nanotube array can also increase the hydrophilic nature of an already hydrophilic surface through functionalization. The super-hydrophobic and capillarity properties of the nanoskin will be illustrated. Overall, synthesis of the long multi-wall carbon nanotube arrays has opened the door for the development of novel sensors, actuators, and multi-functional smart materials.

6174-147, Poster Session

A smart indoor air quality sensor network

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A smart indoor air quality (IAQ) sensor network is being designed and implemented in a real gym building in this project. The proposed IAQ sensor network consists of sensors that supply long term continuous measurements for indoor gas pollutants, particle pollutants, and bio-aerosol pollutants. The design and evaluation methodologies for a comprehensive IAQ sensor network is explored as well as the data collection and analysis methods. The innovation of the study include: 1) systematically examine how to design and evaluate the next generation comprehensive IAQ sensor network; and 2) construction and implementation of a smart IAQ sensor network which includes large variety of IAQ sensors in a real building to supply long-term real time IAQ measurements for the relevant research society and to demonstrate the next generation IAQ sensor network concept. The research would supply guidance to the industry about how to design, implement, and evaluate next generation IAQ sensor network. The collected field data would further assist the research society in the following areas: 1) Next generation building ventilation/decontamination system design and control strategies; 2) IAQ model validation; 3) Human health and productivity related research; and 4) Multi-hazard mitigation, emergency response and disaster preparation.

6174-148, Poster Session

Development of self-contained sensor skin for highway bridge monitoring

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This paper provides an overview of our newly awarded NSF project in CMS Sensor Program. Our research goal is to develop the fundamental concepts, theoretical frameworks and implementation techniques for a self-contained sensor skin in the context of bridge structural safety monitoring. The proposed sensor skin will be composed of (1) active sensing patches for damage diagnosis, (2) RF transceivers for wireless data transmission, (3) embedded planar spirals for contactless power delivery, and (4) unmanned robots for performing inspection routines. The proposed sensor skin will be designed so that it does not require any batteries nor have any wires for power delivery and data transmission. Therefore, the sensor skin patch can be readily mounted to the surface of a bridge structure in a noninvasive manner. Once data are retrieved at the inspection robot unit, concepts and methodologies will be developed so that damage diagnosis can be autonomously performed without relying on prior reference data in the presence of operational and environmental variations that bridges encounter. Finally, realistic environmental and operational conditions that in-service bridges are subject to will be explicitly considered through a field test of a bridge structure.

6174-65, Session 14

An active ionic polymer for dynamic shear stress measurements

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Accurate, dynamic, measurement of wall shear stress in turbulent boundary layers is a challenging task that has been hampered by both spatial and frequency limitations. Improvements in sensor technology are driven by the ever increasing need for novel technologies delivering easy to implement, accurate, robust, time-resolved measurements of skin friction in harsh environments. Turbulent skin friction is the major contributor of viscous drag which is the limiting factor on the range of speed of submarines and ships. Methods for controlling and reducing viscous drag have been developed over the years precipitating the need for quantifying and understanding the dynamics of wall shear stresses. A robust technique for measuring wall shear stress is needed to characterize the structure of the turbulent boundary layers in order to assist the development and assess the effectiveness of viscous drag reduction flow control methods.

The objective of this work is to develop and demonstrate the feasibility of a novel class of direct wall shear sensing technology based on ionic polymer membrane transducers. Ionic polymer transducers are thin polymer membranes that exhibit high sensitivity to mechanical strain. They consist of an ionomer membrane plated with conductive metal layers. These materials exhibit electromechanical coupling under the application of electric fields and imposed mechanical deformation. Characterization of these materials has shown charge-sensing properties similar to those of other active materials such as piezoelectrics. Ionic polymer membranes contain charged side groups that are covalently bound to the polymer chain. A phase separation between hydrophilic “ion clusters” and the hydrophobic backbone results in a charge aggregation that leads to ionic selectivity. As a result, only certain charged groups, either cations or anions, can be transported through the polymer. Charge aggregation due to mechanical deformation gives rise to the transducer sensing capabilities.

The sensors developed herein are aimed at dynamic measurements of skin friction in high-Reynolds number flows. We present a dynamically calibrated sensor, with application to turbulent/separated flows. Dynamic calibration is performed using an oscillating Stokes layer apparatus, providing calibration up to 120 Hz and wall shear stress levels of up to 8 Pascals in water. Errors on the order of 5 % are reported. The sensors have been shown to have minimal sensitivity to pressure and vibration. Temperature does affect the response of the sensor, but can be accounted for based upon the impedance of the transducer. This paper will give an introduction to the mechanism of transduction of these materials, followed by calibration and application to turbulent and separated flows. Sensor applications include measurements of wall shear stress in transitional and turbulent boundary layer flows and separated flow over a circular cylinder.

6174-66, Session 14

Free-vibration studies on cantilever magneto-electro-elastic beam

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Recently the research on magneto-electro-elastic composite as smart materials has gained more importance. These materials have the capacity to convert one form of energy, viz., magnetic, electric and mechanical energy to another form of energy. They exhibit desirable coupling effect between electric and magnetic fields, which are useful in smart or intelligent structure applications and find applications in magnetic field probes, electric packaging, acoustic, hydrophones, medical ultrasonic imaging, etc. These smart materials seem to provide unique capabilities of sensing and reacting to external disturbances, thus helping to design based on performance, reliability and light weight requirements imposed in any modern structural applications.

Studies on static and dynamic behavior of these material in the form of plates and shells have been carried out in literature. Pan[1] has derived exact solutions for three dimensional, anisotropic, linearly magneto-electro-elastic, simply supported and multilayered rectangular plates under static loadings. Sunar et al. [2] have studied the finite element modeling of thermopiezomagnetic medium. Buchanan[3] has studied the behavior of layered versus multiphase magneto-electro-elastic composites. Jiang and Ding [4] have obtained analytical solutions to magneto-electro-elastic beams for different boundary conditions. Annigeri, et al. [5] have carried out static study on magneto-electro-elastic beams for different boundary conditions using finite element method.

From the literature survey, not many studies are found on dynamic analysis of magneto-electro-elastic beam. In the present study, free vibration analysis of magneto-electro-elastic beam made of BaTiO3-CoFe2O4 composite material using finite element method is reported. The beam is modeled using four noded rectangular finite elements. The constitutive equations of Magneto-Electro-Elastic medium involving mechanical, electrical and magnetic fields are used to derive finite element model for the system. The field variables for finite element are axial displacement (u), transverse displacement(w), electric potential (*) and magnetic potential (ψ). The Fortran90 code used for structural analysis of the magneto-electro-elastic beam is validated with results of eigen frequencies of the beam using ANSYS, by treating the beam material as only elastic composite, neglecting piezoelectric and magnetic components. The paper thus highlights the influence of magneto-electric coupling, piezoelectric and magnetic effects on the system frequency, which has significance for developing smart structures.

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6174-67, Session 14

A vibration energy harvesting sensor platform for increased industrial efficiency

T. A. Anderson, D. W. Sexton, GE Global Research

The activities of the "Distributed Wireless Multi-Sensor Technologies" program at the General Electric Global Research Center will be described in this paper. This Department of Energy (DOE) funded research program focuses on the development of a sensor platform for multi-measurand data acquisition and accompanying industrial wireless protocol. Specifically, this program is developing a condition-monitoring device for electric motors and other similar rotating machinery such as vacuum pumps and compressors. By using data published in DOE sponsored publications it is estimated that through increased electric motor monitoring and subsequent improved maintenance and proper sizing, an opportunity of 122 trillion BTU of energy exists to be saved by the year 2020.

To achieve the battery lifetime and life cycle cost requirements for the sensor platform, harvesting ambient energy from the sensor's environment was investigated. For the rotating machinery applications targeted in this program, vibration energy is an attractive potential source of electrical energy. The mechanism by which this vibration energy is converted to electrical power can be one of several schemes such as: electromagnetic, piezoelectric, and electrostatic. Although the best type of vibration energy harvesting scheme often depends on the particular sensor's environment, in terms of the power density, piezoelectric vibration energy harvesting performs well compared to the other technologies and was selected for use in this program.

The piezoelectric energy-harvesting device designed for the sensor package consisted of a 3-layer piezoelectric composite cantilever beam. The top and bottom layers of the beam were piezoelectric PZT-5A and the center layer is a reinforcing metallic shim. The beam is tuned to resonate at one of the critical modes of an electric motor; these modes are a function of the driving AC line frequency and number of poles of the electric motor. Tuning was accomplished through the addition of an adjustable tip mass to the end of the cantilever beam. The electric charge and corresponding current are accessed through wires bonded to the electrode surfaces of the piezoelectric layers. The power conditioning circuitry used to convert the alternating high voltage signal into a stable DC power source and novel battery augmentation power control circuit will also be presented.

As maximum power output as a function of mass and volume are of primary interest, a piezoelectric generator model has been developed and will be presented in this article. The model is in a lumped-element form, with the base excitation acceleration and voltage representing the effort variables, and the tip velocity and electrical current representing the flow variables. As it is a lumped element model, it is only appropriate for conditions where the device is being driven primarily near or below the first vibration mode, which is the case for these motor applications. Optimization studies are then performed on a simple generator configuration to demonstrate the effects of several of the driving geometric and material parameters. Experimental results are also presented to demonstrate the accuracy of the model.

Finally, the results of preliminary field tests using the vibration energy harvesting device and accompanying power conditioning circuit on industrial electric motors will be presented. In these tests it was found that approximately 200 microwatts of regulated 3.3V power could be achieved on a typical industrial 20-hp two-pole electric motor.

6174-68, Session 15

Mechanical-electrical characterization of carbon-nanotube thin films for structural monitoring applications

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Strain is a valuable measure of a material deformation that can be used within damage detection methods. To measure the structural response under eccentric loading for global damage detection, strain sensors can provide detailed information pertaining to localized damage details. For instance, excessive crack formation and weld separation can be easily detected by strain sensors. Although current foil-based strain sensors are capable of measuring strain deformations, their sensitivities (gage factor) are insufficient for localized damage detection. Furthermore, stain gages suffer from temperature dependent drifts and long-term unreliability issues. As such, a miniature prototype strain sensor is presented that addresses the limitation of current technologies. The novel strain sensor is fabricated using the layer-by-layer (LbL) assembly method with single-walled carbon nanotubes to form a thin film-based strain sensor. This sensor has been designed at the molecular length-scale to ensure ideal strain sensor performance optimized for structural health monitoring. Due to the unique linear mechanical-to-electrical properties, high ultimate strength, and high Young's Modulus of thin film SWNTs, the resulting thin film strain sensor exhibits on the order of 10 to 100 times greater sensitivities than traditional foil strain gages. A specific focus of this study is to characterize the mechanical-electrical properties of the proposed carbon-nanotube thin films to ensure sensing properties remain linear and repeatable. A series of thin-film types are fabricated and tested under monotonic and cyclic loading cycles. Both surface mounting of the thin-film and embedment of cementitious structural elements is performed for complete performance quantification.

6174-69, Session 15

Capacitance and phase-angle measurement for estimating moisture content in nuts and grain nondestructively

C. V. Kandala, S. O. Nelson, USDA Agricultural Research Service

The design and performance of an electrical instrument that would be useful in estimating the moisture content (mc) of agricultural products such as grain and nuts nondestructively and rapidly is described here. The instrument measures the capacitance and phase angle of a small sample of the produce, held between two parallel-plate electrodes, at two frequencies 1 and 5 MHz. The measured values were used in a semi-empirical equation to obtain the mc of the sample. The calculated values were compared with the mc values obtained by the standard air-oven method. The estimated values were in good agreement with the standard values. This method is applicable to produce such as corn, wheat, pecans and peanuts. This instrument would be useful in the grain industry for rapid and nondestructive mc measurement.

6174-70, Session 15

An integrated approach to flow sensing and actuation using electrolytic bubbles

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The development of microfluidic systems has advanced the technology for chemical detection, combinatorial synthesis and bioassay. Integration of high density of functional fluidic components onto a single chip is the keys to success for many applications. Utilizing an electrolytic gas bubble based actuation mechanism we have developed a series of microfluidic actuation components including valves, pumps, bi-directional switches, and multiplexers. Recently, we have further extended the bubble-based technology to pressure sensing within closed fluidic channels (static pressure). In this paper, we study the bubble sensors in an open microfluidic channel to measure the pressure in a functional fluidic chip. The bubble sensors are further integrated into a bubble-based actuation fluid distribution system to measure the pressure difference at various stages of a multiple channel network. Integration of bubble-based sensors with actuators into a complex system demonstrates the capability of forming high-density functional microfluidic system using the same electrolytic principle and with ease of microfabrication.

A prototype bubble sensor is designed and microfabricated on silicon chip. An electrolytic bubble sensor was placed in a parallel channel connected with the main flow channel to provide the measurements of open channel pressures in real-time. Since the gas bubbles are non-conductive, the electrical impedance of a region containing a bubble is a function of its relative volume. The bubble size has been shown directly reflects the ambient pressures in microfluidic channels according to two sensing modalities, (1) measurement of the resistance corresponding to the initial bubble size, and (2) measurement of the bubble dissolving rate. The channel impedance response to bubble volume is measured using a phase-lock amplification technique. The pressure dependence of the measured resistance was systematically investigated by applying an inlet pressure ranging from 101 kPa to 115 kPa, while keeping the outlet pressure at atmosphere. Both sensing modalities were implemented to electrically measure the pressure. In terms of the first modality, a range of input voltage pulses was used to vary the initial

volume of a test bubble, and a sequence of pressure measurements were performed for bubbles formed by each given voltage pulse. For the second modality, the corresponding change in the slope of the sensor resistance in response to the change in pressure was measured. For calibration the electrical response of bubble sensor was also compared with direct measurement of pressure using a pressure meter.

To demonstrate the integration capability of bubble based microfluidic technology we have further integrated the bubble sensor into a fluid distribution system. The system contains a single fluid inlet and four outlets. Bubble based fluid actuation components were built into the system to control the fluid flow. Bubble sensors were designed and located at each stage of the fluid channels to measure the pressure difference. These prototype integrated systems are currently being tested for real time pressure sensing in an active fluidic network. Results will be presented in this paper.

6174-71, Session 15

Intelligent diagnosis of mechanical-pneumatic systems using miniaturized sensors

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Fault detection and diagnosis (FDD) is applied to mechanical-pneumatic systems to perform intelligent diagnosis of various faults in the system by utilizing the sensory information commonly found in typical systems, such as pressures and flow rates. In this paper, we present research results on intelligent FDD and characterization of MEMS flow sensor. Vectorized maps are created and calibrated for the purpose of intelligent FDD. In addition, maps of N-manifold can be used for redundancy in diagnosis to improve the accuracy and reliability of the methodology. Such redundant vectorized maps provide for explanation of physical significance of the behavior of the system and the formation or detection of faults. As a result, both physical-based and signal-based intelligent fault detection and diagnosis techniques and methodology can be applied for various types of applications. Experimental results suggest that intuitive choices of parameters and features, based on the understanding of physics of the mechanical-pneumatic system, can be applied with success to intelligent detection and diagnosis of faults. However, many useful features can be selected for purpose of diagnosis but not all of them will be equally effective. Therefore, it is an ongoing effort to design effective and coherent method in the selection of features for diagnosis.

With miniaturization, sensors can be ready made and integrated for intelligent diagnosis. Characterization and modeling of such innovative sensor designs are presented. Using new smart multi-function, telemetric, and integrated sensors as “intelligent nodes” in systems will provide necessary sensory information (e.g., pressure, flow, and temperature) for the next-generation diagnosis. Ongoing results of FDD research as well as analysis and experiments on MEMS sensors will also be presented. The characterization and study of MEMS sensor include: correlation of flow and deflection of sensory element, analysis and modeling, vibration characteristics, fatigue tests, backflow characterization, ... etc. Specifically, the results of fatigue tests provide information and feedback regarding the design and fabrication of the MEMS sensors; more importantly, long fatigue life is essential for the flow sensors to sustain as a transducer. Results of the findings will be presented. An ongoing research on the application of wireless sensors and the addition of wireless means of data acquisition of the current sensors will afford the system capability in remote sensing and diagnosis. The objective is to integrate various types of discrete sensors, as well as the fusion of various miniaturized sensors in a sensor node, for the purpose of intelligent fault detection and diagnosis.

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6174-72, Session 15

Structural health monitoring of composite repair patch in bridge rehabilitation

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In recent years, there are lots of issues occurring on used bridges, aircrafts and other structures, which are threatening the safety of those structures, and accordingly, human lives. To prevent failure of the structures, various measures are being taken. Structure rehabilitations with carbon fiber reinforced composite patches have been adopted and demonstrated to be an excellent way to enhance/repair the structures and prolong their service lives. However, there are still many problems residing in this kind of technology that remains unsolved, such as the failure of the interface between composite repair patches and their host structures. This is a critical issue that needs to be solved for the success of composite patches.

In order to study the debonding between composite repair patches and their host structures, a structure health monitoring scheme was put forward and demonstrated on a concrete bridge model in a laboratory. This system is based on active sensing with diagnostic lamb waves, in which piezoelectric transducers are used as both sensors and actuators. In the test, six SMART Layers, with eight piezoelectirc transducers on each, were integrated with two composite repair strips on the deck slab of the concrete bridge model. For the three diagnostic layers with each composite repair patch, two layers were bonded on the top surface of the patch, and the other is embedded at the interface between the composite repair patch and the deck slab of the concrete bridge model.

The loading procedure of the test included three stages. At first, the bridge model was preloaded to initiate cracks on the deck slabs and then the repair patches were implemented. At the second stage, the load was raised to reach the shear capacity of the girders of the bridge model and then the repair patches were implemented on those girders. At last, the structure was loaded to damage the deck slabs. During all the three stages at different load levels, the initiation and development of the debonding between composite repair patches and deck slabs were clearly revealed by the active sensing system. It demonstrated that the active sensing system employed here is a prompt, robust and precise technique to monitor the debonding process of the composite repair patch for structural rehalibitation. Besides the study of the mechanism of the debonding between repair patch and host structures, an on line health monitoring system can give the user an indication of the structure health status and alerts when it approaches the failure capacity.

6174-73, Session 16

Carbon nanotube films: fabrication techniques and applications to sensing and energy conversion

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Single-wall carbon nanotubes hold great promise for a number of applications due to their outstanding electrical, thermal, and mechanical properties. In particular, thin films of nanotubes are can function as a bulk material with significant materials advantages. Because of the large number of nanotubes in the film, the variability in nanotube types (metallic and semiconducting) is averaged out to produce a relatively homogeneous material.

Nanotube growth is accomplished by chemical vapor deposition (CVD). First, highly uniform thin films of dispersed iron nanoparticle catalysts are deposited on a wafer (Si or quartz) by slowly pulling the wafer out of a solution of nanoparticles in hexane. Nanotube growth occurs at 900 Celsius in a 50/50 mixture of carbon monoxide and hydrogen. An initial growth produces a thin (sub-monolayer) film consisting of tubes with lengths in the 10-100 micron range. To fabricate thicker films, catalyst is applied to the sample again, followed by an additional CVD step. The uniformity of films is seen to improve significantly with this multi-step process.

For use of nanotube films on a wide range of substrates, we have developed a method for transfer of high-quality nanotube films between substrates for applications such as transparent conductive films. This method involves using water-soluble tape to lift the nanotubes from a growth substrate (Si or quartz). The tape is then applied to the target substrate, and then gently removed by dissolving in water. Because the nanotubes are in contact with the target substrate, they remain in contact after the tape is removed.

We are evaluating the performance of nanotube films for applications. First, we are confirming and extending earlier experiments that show production of voltage across bulk samples of nanotubes when they are exposed to fluid flow. Second, we are examining the optical and electrical properties of nanotube thin films, which can act as transparent conducting layers. A significant application of these films is in photovoltaic cells, particularly next-generation solar cells that require highly flexible materials.

6174-74, Session 16

A multiscale field theory for nano/micro sensor materials

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This work aims to formulate a field theory that exactly represents classical N-body dynamics system and is able to work as an alternative to, but is computationally more efficient than, atomic-level molecular dynamics simulation in studying statistical and finite temperature properties of materials, especially in predicting and optimizing multi-functional sensor material behavior for applications in extreme conditions. Multi-length and multi-time scale material behavior is addressed from the viewpoint of crystal dynamics. Atomistic definition and the corresponding field representations of fundamental physical quantities including momentum flux, heat

flux, total and internal energy, temperature, polarization, are obtained and discussed. Time evolutions of conserved physical quantities under external fields are derived in terms of atomic variables, and are expressed in terms of field quantities. This then results in the mathematical representation of conservation laws for the new field theory. Constitutive relations are derived. Strain measures are obtained as a consequence of the formulation. They are homogeneous lattice strain and inhomogeneous internal atomic strains. All material parameters involved are obtained through the formulation. Some numerical examples and potential applications of the field theory are discussed.

6174-75, Session 16

MEMS-based Fabry-Perot vibration sensor for harsh environments

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This paper presents the design, fabrication, testing and analysis of a Fabry-Perot Micro-Opto-Mechanical Device (FPMOD) used as a vibration sensor. The un-cooled high-temperature operational capability of the FPMOD provides a viable low-cost alternative to sensors that require environmentally controlled packages to operate at high temperature. The FPMOD is a passive MEMS device that consists of a micromachined cavity formed between a substrate and a top thin film structure in the form of a cantilever beam. When affixed to a vibrating surface, the amplitude and frequency of vibration are determined by illuminating the FPMOD with a monochromatic light source and analyzing the back reflected light to determine deflection of the beam with respect to the substrate. Because the thin film cantilever beam and the substrate are approximately parallel, this convenient two-mirror cavity arrangement needs no alignment, no reference arm, and no sophisticated stabilization techniques.

The small size of the FPMOD (85-175μm), the choice of materials in which it can be manufactured (Silicon Nitride and Silicon Carbide), and its simple construction make it ideal for harsh high-temperature applications. The integration of micromachined structures with optical interferometric techniques permits the design of sensor systems suitable for localized precision measurements in harsh environments. Micromachined Fabry-Perot devices have gained increased attention for their ability to detect the motion of one mirror with respect to the other. They sometimes rely on highly reflective multilayered mirrors (with or without a metal coating) or a combination of micromachined mirrors with embedded fiber optics. However, the former cannot be used at high temperatures due to coefficient of thermal expansion mismatch and the latter, have a complicated structure and need precise alignment between the micromirrors and fibers.

In this paper, two analytical models are developed to describe the operation of the FPMOD. Furthermore, a complete set of experimental results and the analysis for devices fabricated in low-stress Silicon-rich Nitride (SixNy) are described. Given the Fabry-Perot geometry, an optical transfer function is calculated to permit the substrate motion to be determined from the relative motion of the beam with respect to the substrate. Relative displacements in the sub-nanometer range have been measured and close agreement was found between the measured sensor frequency response and the theoretical predictions based on the analytical models. The magnitudes of these relative displacements are strongly affected by viscous damping (a result of the squeeze film damping in the cavity and the free air damping on the other side of the cantilever) and the performance of the FPMOD is limited by thermal-mechanical noise. Results for a typical set of SixNy FPMOD cantilever beams of cavity height h=3μm and thickness t0=0.45μm are shown.

6174-76, Session 16

Magnetostrictive nanowires as artificial cilia

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Artificial cilia arrays have been fabricated from the magnetostrictive Fe1-xGax alloy system (Galfenol) for use as acoustic sensors. The nanowires were deposited into anodic aluminum oxide templates made by a modified two-step anodization process. The resulting arrays were characterized using scanning electron microscopy, energy dispersive x-ray spectroscopy, x-ray microdiffraction, and vibrating sample magnetometry (VSM). Their crystal structure was bcc Fe with a [110] texture along the growth length. The arrays were arranged in a hexagonal lattice with 40 nm wire diameters and 100 nm center-to-center distance and their coercivities were 156 Oe parallel and 113 Oe perpendicular to the nanowire axes. In order to pick up acoustic signals from the nanowires, GMR layers will being grown into the base of the wires to detect magnetic fields stemming from mechanical motion of the cilia. Here, separate arrays were made to study Co/Cu multilayered GMR nanowires. Co/Cu multilayered nanowires were grown with 5-nm Cu layers and different Co layer thicknesses (6-36nm). The magnetic properties of Co/Cu nanowires were characterized by vibrating-sample method (VSM) magnetometer and the magnetotransport properties of these nanowires were studied as full arrays and in separate lines via patterned electrodes.

6174-77, Session 17

Structural damage detection using sensitivity-enhancing feedback control through eigenstructure assignment

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Structural damage detection based on changes in vibration characteristics has received much attention in recent years. Among all the vibration-based detection methods, the ones based on changes in natural frequencies or frequency response functions are considered to be the easiest to implement. However, such frequency shift-based damage detection has severe limitations in practical applications; namely, 1) the number of natural frequencies that can be measured is normally much smaller than the degrees of freedom required for accurate damage identification, which leads to an underdetermined problem; and 2) modal frequencies can be insensitive to small changes in local mechanical properties thus it is difficult to measure modal frequency changes accurately in the presence of measurement noise.

In order to increase the modal frequency data available for sensitivity-based model updating, researchers have proposed a variety of methods, such as the technique of adding a mass or stiffness to create new eigendata [1,2], the concept of using a virtual passive controller to generate additional closed-loop modal frequencies [3], and the method of integrating tunable piezoelectric transducer circuitry to enrich the frequency response measurement [4,5]. Although these techniques help to improve the performance of damage detection using sensitivity-based model updating, the credibility of the detection can still be critically threatened by the presence of measurement noise, especially when the frequency changes are insignificant due to small damage. Therefore, a method which helps to enhance the sensitivity of modal frequencies relative to structural damage is highly demanded.

The concept of sensitivity enhancing control (SEC) was introduced by Ray and Tian [6] to improve sensitivity of closed-loop resonant frequencies towards stiffness reduction and mass loss. A damage-sensitive pole placement technique is employed to design the feedback control laws for sensitivity enhancement, and numerical simulations for a cantilevered beam with single input demonstrated that the sensitivity of frequency-shift to stiffness reduction can be enhanced by reducing the natural frequencies of the closed-loop system from those of the open-loop system.

The objective of this paper is to advance the state-of-the-art of the concept of sensitivity enhancing control (SEC) for damage identification. More specifically, the method of eigenstructure assignment is utilized to design the feedback control laws to further enhance the sensitivity of frequency-shift to structural damage and improve the performance of sensitivity-based damage detection.

From the eigenvalue sensitivity analysis of the closed-loop system, which is defined to be a multi-variable asymmetric damped system, it is found that the eigenvalue sensitivity depends on not only the closed-loop system eigenvalues themselves, but also the eigenvectors of the closed-loop system. Therefore, the eigenvalue sensitivity can be further improved by appropriately assigning both the eigenvalues and eigenvectors of the closed-loop system.

An optimization problem can be formulated to find the optimal achievable eigenvectors of the closed-loop system when the closed-loop eigenvalues are assigned. From the theory of singular value decomposition (SVD), the achievable closed-loop eigenvector can be expressed as a linear combination of a set of orthogonal basis vectors, which spans the null space of the matrix on which the SVD is applied. Therefore, the design variables are the linear combination coefficients used to express the set of closed-loop eigenvectors selected to do eigenvector assignment. The cost function can be defined to be the summation of either one column or all the terms of the sensitivity matrix obtained from the eigenvalue sensitivity analysis of the closed-loop system. Genetic algorithm (GA), an optimization technique guided by the principle of natural genetic systems, is used to perform the optimization.

To illustrate the proposed concept, damage identification of a beam structure integrated with piezoelectric transducers is used as an example. Based on the results of numerical simulation, it is shown that the optimized sensitivity enhancement controller through eigenstructure assignment benefits the damage detection in the sense that it can further enhance the sensitivity of frequency-shift relative to structural damage, thus making the frequency-shift based damage identification method capable of detecting small damage and be more immune to measurement noise.

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6174-78, Session 17

Multivariate statistical analyses for damage detection of engine bladed-disks

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The timely detection of damage in aero-engine bladed-disks (e.g., compressor fans) is an extremely important research topic. Currently, blade damage/crack detection is mostly exercised by using eddy current and ultrasonic technologies. These methods, while having good reliability, need significant amount of human involvement, have narrow field coverage and are position sensitive. It is also difficult to implement these methods as true in situ approaches. Measuring the vibratory responses of bladed-disks under operating condition, on the other hand, has become possible with blade-tip timing (BTT) sensing technology, which provides a new opportunity for in situ damage detection. While various damage detection schemes for general structures using vibration signals have been explored, detecting damage in a bladed-disk is significantly more challenging. Bladed-disks have high modal density and, particularly, their vibration signals are subject to significant uncertainties due to manufacturing tolerance (blade-to-blade difference or mistuning), operating condition change and sensor noise. Clearly, any deterministic detection approach could suffer from large number of false alarms.

In this study we present a new methodology of damage detection using the bladed-disk vibratory responses during spin-up or spin-down operations which can be measured by BTT sensing technology. A simplified bladed-disk model with crack damage is developed for the analysis and algorithm development. The bladed-disk has inherent mistuning and the responses measurements are contaminated by noise. We first apply a principle component analysis (PCA)-based technique for data compression, feature extraction, and denoising. The non-model based damage detection is achieved by analyzing the vibratory response changes between the intact structure and the damaged one in the directionality. Following that, multivariate control limit using Hotelling's statistic is used to interpret which characteristic or group of characteristics of the directionality is out of control that corresponds to abnormal signal condition. This allows us to declare damage occurrence under various noise/uncertainty with deterministic confidence level. A series of case studies are performed. Specifically, the effects of bladed-disk and excitation properties, noise level, mistuning level, damage severity, and the size of baseline dataset on the detection sensitivity are discussed. Qualitative understandings on sensor data analysis are obtained. The analyses show that this multivariate statistical analysis based on frequency-responses can successfully detect small damage under very significant structural uncertainty and noise, which provides a new means for on-line bladed-disk damage detection.

6174-79, Session 17

Comparative analysis of distributed mass micromachined gyroscopes fabricated in SCS-SOI and EFAB processes

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This paper presents our preliminary results on comparative analysis of wide-bandwidth micromachined gyroscopes. The devices have been fabricated in two distinctive MEMS fabrication processes and experimentally characterized. The design concept is based on forming multiple drive-mode oscillators with incrementally spaced frequencies, distributed symmetrically around the center of a supporting frame. The distributed drive-mode oscillators are driven in-phase radially, and are structurally constrained in the tangential direction with respect to the supporting frame. In the presence of an angular rotation rate about the z-axis, a sinusoidal Coriolis force at the drive frequency is induced on each proof mass. Each of the induced Coriolis force vectors lie in the tangential direction, combining to generate a resultant torque on the supporting frame. The net Coriolis torque excites the supporting frame into torsional oscillations about the z-axis, which are detected by sense capacitors for angular rate measurement.

Two batches of prototypes have been fabricated using in-house single crystal silicon on insulator (SCS-SOI) bulk-micromachining process and EFAB(tm) process commercially available from Microfabrica Inc. The SOI fabrication process relies on deep-reactive ion etching (DRIE) through the 100μm device layer of a silicon-on-insulator wafer and front-side release of the structures by etching the buried Oxide layer in HF solution. EFAB(tm) process consists of sequential deposition and planarization of patterned metal structural layers on an alumina substrate. Twenty 10um thick layers of Ni-Co were used allowing creation of 200μm thick 3D structures.

Detailed system identification was performed using electrostatic actuation algorithms. Lumped parasitic resistance and capacitance was identified and the feedthrough was filtered out from the measured frequency response allowing for identification of mechanical parameters. For the SOI devices the frequency separation of the resonators was observed to provide over 600Hz operating frequency region with leveled output in atmospheric pressure. However, the leveled region showed a maximum variation of 17.2% in the total response due to nonuniform frequency separation. After electrostatic tuning of the parallel-plate oscillators for 10Hz spacing, the close spacing of the drive-mode resonance frequencies allowed all of the resonators to be excited together, to jointly generate a resultant Coriolis torque with a leveled region of over 90Hz. Identical prototypes of micromachined gyroscopes have been fabricated in EFAB(tm) process. The devices have been experimentally characterized. The sense mode resonant frequency was identified to be ~880Hz, and was demonstrated to be effectively tuned by negative electrostatic spring effect to match the drive mode frequency bandwidth. Sense mode bandwidth was detected to be 3Hz in air and 1Hz at 30mTorr vacuum, resulting in quality factors of 250 and 850, respectively. These numbers are in good agreement with quality factor values observed in similar SOI devices. Thus, we demonstrated that EFAB process can be successfully used for inertial sensors and structural damping of electroplated No-Co compound is not a limiting factor. Experimental investigation of the effect of temperature on the structural parameters of the prototypes showed that the resonant frequency drops with temperature. Increase of temperature from 25C to 125C resulted in ~0.5% resonant frequency reduction and slight increase in damping coefficient. Similar SOI devices are currently experimentally characterized, including the experiments on effects of thermal load on device response and evaluation of the scale factor.

6174-80, Session 17

Active sensing and characterization of nonlinear damages by modulated phases and envelopes of scattered waves

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In this paper, a novel sensing methodology to detect and characterize early damages such as loose bolts in a joint and breathing cracks is developed, being inspired by the pioneer work by Mita et al. The proposed sensing system consists of several PZT patches attached on the structural surface, one of which acts as a transmitter of ultrasonic harmonic wave. The incident harmonic wave is then scattered by the damage and received by the other patches. When the structure is subjected to the operational or ambient load, it vibrates, and the inherent damages introduce some nonlinear effects into the structural dynamics. This nonlinearity is observed as the phase- and amplitude-modulation of the scattered waves due to the changes in the scattering characteristics synchronous with the structural vibraiton. By investigating the relationship between the phases of the incident and scattered waves, and the relationship between the structural vibration, which is obtained by low-pass filtering of the observed signals of PZT patches, and the modulated phases and envelopes, and the the nonlinear characteristics of the damages can be identified both in time-domain and in frequency-domain. Some experiments using a bolted beam and a cracked beam are conducted for illustrative purposes.

6174-82, Session 17

Design and control of electro-rheological fluid-based torque generation components for use in active rehabilitation devices

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In this paper we present the design and control algorithms for novel electro-rheological fluid based torque generation elements that will be used to drive the joint

of a new type of portable and controllable Active Knee Rehabilitation Orthotic Device (AKROD) for gait retraining in stroke patients. Two different torque generation components of the device are described: a resistive (variable damper) and an active (torque actuator) component. Both components will be relied upon in order to avoid knee hyperextension and foster re-learning of a knee flexion pattern during stance. Also, both components will be relied upon to correct stiff-legged pattern, defined as limited knee flexion during swing.

The AKROD is composed of straps and rigid components for attachment to the leg, with a central hinge mechanism where a gear system is connected. The key features of AKROD include: a compact, lightweight design with highly tunable torque capabilities, full portability with on board power, control circuitry, and sensors (encoder and torque), and real-time capabilities for closed loop computer control for optimizing gait retraining. The variable damper component is achieved through an electro-rheological fluid (ERF) element that connects to the output of the gear system. Using the electrically controlled rheological properties of ERFs, compact brakes capable of supplying high resistive and controllable torques, are developed. Concentric cylinders, acting as electrodes supply the necessary electric field to activate the fluid, which changes its consistency from that of a fluid to a thick viscoelastic gel. Simultaneously, these plates, when charged and rotating, act as surfaces upon which the activated fluid creates a shear force in response to rotation. An advanced hybrid actuator concept that uses the ERF brake concept with the addition of electro-magnetic actuators to actively generate torque, will also be described.

A preliminary prototype for AKROD v.2 has been developed and tested in our laboratory. AKROD's v.2 ERF variable damper component was tested in laboratory experiments using our custom made ERF Testing Apparatus (ETA). ETA provides a computer controlled environment to test ERF actuators in various conditions and scenarios including emulating the interaction between human muscles involved with the knee and AKROD's ERF actuators / brakes. In our preliminary results, AKROD's ERF variable damper component was tested in closed loop torque control experiments. A hybrid (non-linear, adaptive) Proportional-Integral (PI) torque controller was implemented to achieve this goal. Several experiments were performed with a large number of torque values and several disturbances were introduced such as introducing unexpected external torques to the system. The controller was able to almost instantly compensate these torque disturbances and maintain very accurately the desired torque value.

6174-83, Session 18

Ultrasonic guided-wave monitoring of composite bonded joints using macro fiber composite transducers

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The monitoring of adhesively-bonded joints through the use of ultrasonic guided waves is the general topic of this paper. Specifically, composite-to-composite joints representative of the wing skin-to-spar bonds of Unmanned Aerial Vehicles (UAVs) are examined. This research is the first step towards the development of an on-board structural health monitoring system for UAV wings based on integrated ultrasonic sensors. The study investigates two different lay-ups for the wing skin and two different types of bond defects, namely poorly-cured adhesive and disbonded interfaces. The guided wave propagation problem is studied numerically by a semi-analytical finite element method that accounts for viscoelastic damping, and experimentally by utilizing macro fiber composite (MFC) transducers which are inexpensive, flexible, highly robust, and viable candidates for application in on-board monitoring systems. Based upon change in energy transmission, the presence of damage is successfully identified through features extracted in both the time domain and discrete wavelet transform domain.

A "passive" version of the diagnostic system is also demonstrated using the MFC sensors for detecting and locating simulated active damage in the bond. Difficulties associated with damage location in anisotropic CFRP composites are overcome by exploiting the uni-directionality of the MFC sensors; yielding a damage location algorithm which is independent of wave speed.

6174-84, Session 18

Lamb-wave behavior in bridge girder geometries

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Lamb waves in plates and in cylindrical pipes have been the subject of extensive study, largely because they propagate great distances with little attenuation, and can therefore be used to detect flaws. In this paper we report finite element simulations and experimental studies of Lamb waves in steel bridge girder geometries, with the purpose of determining the extent to which a transducer may illuminate a segment of a plate girder, and the direction and length of cracks that might be expected to return an echo for flaw detection.

In our studies the Lamb waves are generated by PZT wafer-type transducers mounted on the girder web, driven by a tone-burst transient excitation; the pulse center frequency is chosen to yield a frequency-thickness product of roughly 1 MHz-mm, at which the group velocities of the S0 and A0 waves are well separated, and at which waves in higher modes are theoretically absent. Three-dimensional, transient dynamic, finite element simulations were performed using FEMLAB. The simulations show that transmission at the web-flange joint creates guided waves in the flanges that travel at different velocities from the Lamb waves in the web, and that reflection at the web-flange joint creates a largely straight-crested wavefront for the Lamb waves in the web remote from the source. Simulation studies also illustrate the acoustic influence of plate girder transverse stiffeners, which is observed to be relatively small. Similarly, the simulation studies show the reflections produced by typical fatigue cracks, both for primary stress-induced and for distortion-induced crack geometries.

A welded steel plate girder laboratory specimen was fabricated with proportions typical of highway bridge members, at approximately half-scale. The web height is 920 mm and thickness is 3.2 mm, for a representative height-thickness ratio of 288; the flange width is 100 mm and thickness is 6.4 mm, for a representative width-thickness ratio of 16. Small PZT transducers, roughly 6.4 x 6.4 x 0.6 mm, excited at less than 10 V, produce ample signals over paths several meters in length. We compare simulation results and experimental measurements for Lamb wave illumination of the plate girder segment. We discuss the influence of acoustic coupling at the web-flange joint, for the case of a rolled girder and for the case of a fillet-welded plate girder. We also discuss the detection of cracks, simulated experimentally by saw cuts of varying dimensions in the laboratory girder specimen.

6174-85, Session 18

Cylindrical guided waves for damage detection in underground pipes using wavelet transforms

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Wavelet analysis is a powerful signal-processing tool. This technique is being used for signal de-noising, signal compression, detecting frequency breakdown of signals etc. In this research work, wavelet transform technique is applied on cylindrical guided waves propagating through underground pipes for detecting damages in pipe walls. In this underground pipe inspection study, cylindrical guided waves are generated and received for both damage-free and damaged pipes using piezoelectric transducers. An algorithm, based on Continuous Wavelet Transform (CWT) is applied to analyze the received signals from the damaged and undamaged pipes. In the Continuous Wavelet Transform (CWT) technique different parameters of the mother wavelet function are varied to optimize the function that is best suited for damage detection. A comparative study of the effect of different mother wavelet functions on the received signals for the pipe wall damage detection is presented in this paper.

6174-86, Session 19

Unsupervised learning algorithm for high-speed defect detection in rails by laser/air-coupled non-contact ultrasonic testing

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Recent train accidents and associated direct and indirect costs including cost of repair of equipment and infrastructure as well as delay and death/injury costs, have reaffirmed the need for developing rail defect detection systems more effective than those used today. In fact, rail defect detection has been identified as a priority area in the U.S. Federal Railroad Administration 5-year R&D plan. This paper proposes an unsupervised learning algorithm for defect detection in rails. The algorithm is used in a non-contact inspection system that is targeted to the detection of transverse-type cracks in the rail head (including transverse fissures and detail fractures), notoriously the most dangerous flaws in rails. The system uses ultrasonic guided waves that are generated by a pulsed laser and are detected by air-coupled sensors positioned as far away as 76 mm (3") from the top of rail head. The inspection ranges is at least 500 mm (20") for surface head cracks as shallow as 1 mm. Fast data output is achieved by processing the ultrasonic defect signatures by Wavelet Transform algorithms. The features extracted after wavelet processing are analyzed by a learning algorithm based on novelty detection. This algorithm attempts to detect the presence of damage despite the normal variations in ultrasonic signal features that are found in a field test.

6174-87, Session 19

Guided-wave signal processing using chirplet matching pursuits and mode correlation for structural health monitoring

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Structural health monitoring (SHM) using guided waves (GWs) excited by an onboard transducer network has been the subject of much study in recent years, owing to their great potential as an effective solution for in-situ damage prognosis in several initial laboratory studies. It essentially involves transducers emitting high frequency tonebursts to excite guided waves in the structure. The analysis of the wave signals in the structure will provide information about damage, if present [1]. One key issue that has not been adequately addressed in the literature is that of an effective signal-processing algorithm capable of resolving overlapping reflections and distinguishing between the various modes that can arise due to scattering from defects. For example, in a flat plate, at any excitation frequency, there are at least two guided-wave modes that can be scattered from a defect, even if only one pure mode was incident on it. Also, the modes may be dispersive, i.e., their wavespeeds vary with frequency uniquely for each mode. Furthermore, for real-time cost-effective onboard signal processing, it is highly desirable that the algorithm be computationally efficient. Conventional solutions to this problem from the field of Non Destructive Testing (NDT) are in the form of some time-frequency representation, wherein the correlation of time-frequency ridges with the GW dispersion curves is used to determine the mode (see, for example, [2]-[5]). All continuous squared time-frequency representations (TFRs), including the spectrogram and the scalogram, which are derived from the short-time Fourier transform (STFT) and continuous wavelet transform (CWT), respectively, can be expressed as a time-frequency averaging of the Wigner-Ville distribution [6]. These suffer from the drawbacks of difficult automated post-processing as needed in SHM, having to compromise between time and frequency resolutions or between time-frequency resolution and interference terms, high computational cost (except those algorithms that can be implemented using fast Fourier transforms, such as the STFT and CWT), and poor ability to resolve overlapped reflections. In addition, these are more suited for broadband signals, while in GW SHM, usually narrow-band signals are used, in order to minimize signal spreading due to dispersion. Another solution proposed by some researchers ([7], [8]) is the use of a large array of sensors to separate modes using a 2-D Fourier transform of the individual element signals. This approach, however, requires a large number of very closely spaced transducers to avoid aliasing and sophisticated hardware to process the array signals.

With the above in mind, this work sought new techniques to process GW signals from a single sensor, which could overcome the limitations posed by conventional approaches. A chirplet matching pursuit-based algorithm developed by Gribonval [9] is employed to isolate individual reflections from scattering sites, in terms of their time-frequency location and spread, and a novel mode-correlation check is then used to identify the GW mode. The matching pursuit approach in signal processing was introduced by Mallat and Zhang [10]. This “greedy” algorithm iteratively projects the signal onto a large and redundant dictionary of waveforms and chooses a waveform from that dictionary that is best adapted to approximate part of the waveform. Thus, it decomposes the signal into a linear expansion of waveforms chosen to match best the signal structure. In the original paper on matching pursuits [10], an efficient algorithm using a Gaussian modulated time-frequency atoms dictionary (which have stationary time-frequency behavior) is described and this has been explored by some researchers for GW signal analysis in non-dispersive signals without worrying about mode classification [11], [12]. However, the atoms in this dictionary are ill suited for analyzing dispersive signals, which have non-stationary time-frequency behavior. The algorithm in [9] is a computationally efficient way to decompose the signal into chirplets, which are Gaussian modulated time-frequency atoms with linear time-frequency behavior, and consequently, these are better suited for capturing dispersive signals, particularly when the excitation bandwidth is small. Furthermore, this decomposition can be used to construct a TFR that is free of interference terms unlike conventional TFRs. This approach is also robust to noise in signals. Noise in a signal is uniformly distributed across the entire time-frequency plane, and hence its effect is severely diluted when the signal is decomposed into chirplets. This is because the original noiseless signal is concentrated in certain portions of the time-frequency plane and is well approximated by chirplets.

After decomposing the signal into elementary chirplet atoms, the GW mode of each atom must be identified. For this, there are two possibilities. If the dispersion curves have slopes with opposite sign, i.e. if for one, the group velocity increases with frequency while for the other, the group velocity decreases with frequency, then the chirp rates estimated from the matching pursuit algorithm can be used to identify the mode. If however, this is not true, then a rigorous mode correlation check can be used. In the latter, using the waveform parameters from the matching pursuit, a waveform for each mode type is generated based on the group velocity curves. In this case, it is assumed that the defect is point-scatterer emitting circular crested waves. The cross-correlation coefficient between the original signal and the normalized waveforms corresponding to each mode is then used to identify the guided wave mode. A 2-D FEM simulation was run for the case of an isotropic plate. In this case, the actuators were excited in the S0 mode with a 2.5 cycle Hanning-windowed sinusoidal toneburst at 275 kHz, and the resulting surface axial strain waveform at the center of the plate was recorded and corrupted with noise. Since in the frequency range of excitation the dispersion curves have slopes with opposite signs, by comparing the difference in slopes between the chirp atoms and the local slopes of the possible modes (in this case A0 and S0) at the time-frequency centers of the atoms, the modes were correctly identified and the radial location of the notches found with a maximum deviation of 0.5 cm. It is worth noting that the technique was capable of separating an A0-mode reflection from the notch at 6 cm and a S0-mode reflection from the notch at 10 cm, which were overlapped with each other, and could not be separated using a spectrogram. However, at higher plate thickness-excitation frequency products, the dispersion curves have slopes with the same sign and the latter approach is preferable to identify the modes correctly. This was tested successfully in an experiment with a 3.15-mm thick plate excited at 375 kHz (in this case, three modes were possible, viz., A0, S0 and SH0). Once the mode type is established, from the group velocity curve for each mode, the defects can be triangulated. The relative contributions of each mode from a scattering location can be used to characterize the nature of the defect. An extension of this algorithm is being explored to cover GW SHM in composites as well as under varying external conditions (e.g., temperature). Detailed results from these experiments and more in-depth analysis of this approach will be presented in the final paper.

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6174-88, Session 19

New statistical algorithm for modal interpretation of measured sensor data with application to marine risers

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A new method is proposed to detect changes in the mean and variance of individual modal frequencies of measured structural response acceleration data. Sensor networks are used in diverse applications across a broad range of disciplines. In

civil, mechanical and aerospace engineering, sensor networks can be used for monitoring or assessing the current state of a structural system. The voluminous data provided by these networks often needs to be reduced into some more useful form to better understand the structural system or to support decision making, and can be reduced either by real-time or through post-processing. This processing enables estimation of useful structural response characteristics: in this case, knowledge of individual modal frequencies. Changes in modal frequencies can be useful for detecting changes in structural properties, which may include structural damage. The proposed new methodology is general, and so may find diverse future applications across a broad range of disciplines involving sensors integrated with engineered structures.

In the proposed new method, a power spectrum of measured two-dimensional structural response resulting from Fourier transformations is interpreted as being a series of individual modal responses. Each modal response is isolated over a frequency range in the power spectrum and treated independently as a statistical distribution. Spectral moments are directly calculated from each of these distributions, which are generally non-Gaussian. A novel inverse application of the Hermite transformation is introduced to convert the non-Gaussian distribution into the Gaussian, so that conventional statistical tools can be applied. The resulting statistical data is used to quantify shifts in the mean of individual modal frequencies and the spread of response energy around each mean.

A historically intractable problem, vortex induced vibration of marine risers, is addressed with the new method. Marine risers are the long slender cylindrical pipes between the sea-floor and an offshore oil production structure on the ocean surface, which sometimes have unsupported vertical spans of up to 10,000 feet. Ocean currents occasionally give rise to vortex wakes along the riser, which excite riser vibrations normal to the direction of current flow. The phenomenon is broadly known as vortex induced vibration, or VIV. The VIV data in this example has been measured on a full-scale drilling riser using an array of accelerometers, each of which is located at presumed anti-nodes of the riser vibration. Modal frequencies resulting from acceleration response time-histories measured by individual sensors are analyzed. These modal frequencies are important because they can later be used to infer an important hydrodynamic property: the mass of the water entrained along the vibrating riser. Application and results of the new statistical method are also compared with conventional tests of statistical stationarity: the runs test and the reverse arrangements test. These conventional tests check for stationarity of the entire process, while the new method can be used to find changes in both the frequency location and energy spread of individual modal response frequencies.

6174-89, Session 19

Chaos theory analysis of cable-stayed bridge vibrations

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Cable-stayed bridges are a recent development in bridge structural design in which the cables meet the bridge deck at an acute angle rather than perpendicularly. Some early cable-stayed bridges have exhibited large amplitude stay cable oscillations. One such bridge, the Fred Hartman Bridge across the Houston Ship Channel in Texas displayed two different modes of vibration: a local mode involving independent motion of individual cables and a global mode, in which the cables vibrated collectively under certain wind and rain conditions. This abrupt shift in mode as a function of a change in environmental parameters suggests chaotic behavior. Analysis of the probability density function of maximum accelerations of the cables typically showed a fractal power law distribution at lower values, but also some sharp peaks in the tails. The Lorenz Map plots of the data also indicated two regimes: a dissipative one at lower acceleration values and chaotic behavior beyond a critical acceleration value. The plots also imply that the chaotic system is nearly two-dimensional. The working hypothesis is that steady winds impose additional stresses on the stay cables that push them over the boundary into the chaotic regime where random impulses from falling raindrops become amplified into cable oscillations.

6174-90, Session 19

Experimental verification of a GPS network: characterization and removal of multipath effects

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The inspection and maintenance of aging Civil Infrastructure Systems (CIS) in the United States have placed a heavy economic burden on society, requiring more efficient and effective inspection and assessment means. In response to this need, research in the area of structural health monitoring (SHM) has grown rapidly. Typically SHM has been accomplished using more traditional sensors such as accelerometers and strain gages, which cannot provide a measure of the absolute global displacements of a structure. However, such measures can be obtained using Global Positioning Systems (GPS), which provide a means to capture not only the dynamic displacements of a structure in real time, but also static displacements resulting from settlement, thermal expansions, permanent offsets and the background component of wind-induced response - all potentially critical for an overall structural assessment.

In order to fully verify GPS as a suitable technology for SHM, a comprehensive calibration study was performed at the University of Notre Dame. A GPS network was established, consisting of a reference station and two rover stations. In addition to the GPS units, two traditional SHM sensors were used to benchmark the GPS performance: a terrestrial positioning system (TPS) and an accelerometer. All the sensors were used to track motions imparted by a small, deployable shake table, simulating signals ranging from simple sine waves to building motions under the action of wind and earthquakes. The performance of GPS in comparison to these traditional sensor technologies is provided in this study.

Through previous experience with GPS in the City of Chicago (Kijewski-Correa and Kareem 2003), the second author noted several unresolved issues affecting performance in urban environments, including potential accuracy losses in real time kinematic (RTK) mode, the impact of the nonstationarity of the GPS reference site and the effects of multipath interference. The latter issue is most concerning in deployments in dense urban zones, producing spurious long-period distortions in the GPS displacement data. In order to better characterize multipath effects and develop means for their removal from processed data, the testing program at the University of Notre Dame was expanded to include a controlled multipath simulation phase, where distortions were generated using an aluminum reflector. The findings of these investigations and the subsequent development of a multipath removal scheme are presented herein. With this removal strategy in hand, GPS now promises to be an effective technology for SHM, even in dense urban areas.

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6174-91, Session 20

Damage detection of structures using support vector machines under various boundary conditions

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Many Structural Health Monitoring (SHM) methods have been proposed for the purposes of reducing maintenance cost and/or assuring performance of civil structures. The objective of this research is to propose a damage detection system that can obtain the detailed damage information by use of the minimum number of sensors. The proposed system minimizes the possibility of incorrect judgments. Modal frequencies of a structure are used for pattern recognition in the proposed method. Changes in multiple natural frequencies can reveal the spatial information on the location of damaged stories. Typically only two vibration sensors, one on the roof and the other on the ground, detecting a single input and a single output for the structure are needed to determine modal frequencies. Out of many pattern recognition tools, we propose to use the Support Vector Machine (SVM). This technique was found effective in our system. Our previous studies demonstrated that the proposed damage detection method worked well for simple models such as shear structures and bending structures. However, real buildings have various boundary conditions at their supports. In this study, the SVM technique was applied for damage detection of structures with various boundary conditions. The feature vectors for construction of SVMs are generated based on the model of a structure. Then locations of structural damage are detected by inputting the measured structural vibration data into the SVMs. From simulation, it was found that the influence of the change in boundary conditions on the lower modes is larger. We performed an experimental study on damage detection of power distribution poles with overhead wires. We proposed a method for determining the boundary conditions of the poles and verified this method based on measured vibration data. We demonstrated the effectiveness of the proposed method in detecting damage in the poles through simulation.

6174-92, Session 20

Structural damage detection and assessment using acceleration feedback

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This paper presents a method for structural health monitoring using acceleration measurements. In a previous study a method for detecting, locating and quantifying structural damages has been developed by directly using the time domain structural vibration measurements. In this paper acceleration, rather than displacement and velocity, measurements are used since it is more practical. Using acceleration measurements is also more difficult since the effects of different damages can not be decoupled completely as in the cases of displacement and velocity measurements. Two approaches of dealing with this issue are presented, one using a higher order system and another in which monitors are designed with certain robustness. Some main drawbacks of each approach are included and discussed. The effects of noise measurements are considered as well. Examples of three-story and eight-story models are presented to demonstrate the effectiveness of the proposed method.

6174-93, Session 20

Damage detection with spatially distributed 2D continuous wavelet transform

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The response of a structure is usually modified when the structure is damaged, especially in the vicinity of the damaged zones. Such local perturbations are generally very small but they can be easily extracted by using wavelet transform techniques. To this end, a two dimensional (2D) Continuous Wavelet Transform (CWT) algorithm is proposed that can use data from discrete sets on nodes and provide spatially continuous variation in the structural response parameters to monitor structural degradation. Combined with an embedded sensor network to provide nodal response signals, this algorithm has potential for Structural Health Monitoring (SHM). The advantageous features of this algorithm are its reliance on local data, its ability to yield spatially continuous information, and its limited communication and computation requirements. The feasibility of the proposed method is demonstrated using two illustrative examples: one is based on the crack-tip strain field of a plate subjected to biaxial load (analytical solution), the other is based on the deflection field of a simply supported plate with defects subjected to static or impact transverse loading (FEM solution). For each case, a set of discrete data is used to simulate the nodal sensor response, and then the 2D CWT is applied to detect damages. The damage positions are accurately located and the damage severity is qualitatively assessed. In addition, a 3D data case (2D spatial signal with time history) is examined to demonstrate the feasibility of using 3D CWT for SHM.

6174-94, Session 20

Damage identification for nonlinear dynamic system using adaptive Monte Carlo filter

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The recursive filters such as Kalman filter and Monte Carlo filter(MCF) do not have a sufficient time tracking ability for non-stationary change of structural parameters due to damage, crack in concrete surface, and deterioration of members, because the identification for the system with non-stationary dynamic characteristics depends upon the past observation data. Thus, results from identification appear low accuracy for structural parameters. To overcome this problem, the new algorithm of adaptive MCF was developed by using the concept of variable forgetting factor.

To conduct the identification for a system with non-stationary dynamic characteristics - the system parameters abruptly change - under the strong earthquake motion, the developed adaptive MCF is applied to a dynamic system. The concept of the forgetting factor multiplying to the process and observation noises is applied to Monte Carlo filter. The forgetting factor is defined as the ratio of the probability density functions of a baseline noise distribution and its hypothetical distribution. The validity and effectiveness of the proposed method has been verified by using various values of the forgetting factors for identification of dynamic characteristics of the shear building model as a nonlinear dynamic system.

6174-95, Session 20

Hybrid Health Monitoring of Structural Joints using Modal Parameters and EMI Signatures

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During the past decades, a significant amount of research has been conducted in the area of structural health monitoring (SHM) via changes in dynamic modal characteristics of a structure. A suitable SHM system is required to sense structural response signals, to extract useful features, and to discriminate the features for identifying damage states of a structure. A promising SHM system, to date, is a combination of vibration-based techniques and electro-mechanical impedance (EMI)-based techniques. The most appealing feature associate with using vibration-based techniques is that modal parameters such as natural frequencies and mode shapes are simple to measure and to utilize for a prompt, global, diagnosis. Also, the EMI technique which uses smart PZT patches has emerged as a valuable, local, SHM tool to detect incipient-type damage such as cracks or loosened connections at local points of a structure.

In this study, a hybrid health monitoring scheme of structural joints using modal parameters and EMI signatures is presented. A beam joint model is experimentally tested to measure accelerations and EMI signals during a period of time. A series of damage and temperature scenarios are designed to simulate various situations for which the connection joints can experience under the service. As the vibration-based techniques, a statistical pattern recognition model is used to alarm the occurrence of damage, and a damage index method based on modal strain energy concept is implemented to detect the location of damage. Also, EMI signatures are sensed before and after the damaging scenarios by monitoring changes in resonance frequencies and RMS magnitudes of impedance signals of Fourier-transformed EMI signals.

6174-96, Session 21

Hybrid optical fiber sensor system based on fiber Bragg gratings and plastic optical fibers for health monitoring of engineering structures

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In this paper, packaged fibre Bragg grating (PFBG) sensors were fabricated by embedding them in 60mm X 10mm x 1mm carbon-fibre composites for robustness which were then surface-bonded to a number of substrates to investigate their strain monitoring capability. The response of these packaged sensors under tensile, compression and static loadings were compared to bare FBGs and electrical strain gauges located in the vicinity. The effective strain-optic coefficient of the packaged sensor was also compared with the non-packaged version. These PFBG sensors were then attached to monitor the loading of an I-section steel beam and an overhead crane system. These realistic structures provide a platform to assess the potential and reliability of the PFBG sensors when used in harsh environment. The results obtained in this study gave clear experimental evidence of the difference in performance between the coated and uncoated PFBG fabricated for the study.

In another experimental set-up, bare FBG sensors were surface-bonded to a CFRP-wrapped reinforced concrete beam which was then subjected to 400 thousand cycles under a flexural loading to assess their long-term survivability. Plastic optical fibre (POF) sensors were also attached to the side of the 3 meter composite-wrapped concrete beam to monitor the progression of cracks developed during the fatigue test. POF vibration sensor was also attached to monitoring the flexural loading of the beam. The results showed excellent long-term cyclic-load tolerance by the FBG sensor and the potential of the POF sensor to detect and monitor the propagation of the crack tip and flexural loading.

6174-97, Session 21

An integrated FBG sensing system for bridge health monitoring

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Thanking to its distinguishing advantages including wavelength multiplexing capability, miniature size, high sensitivity, immunity from electro-magnetic interference and etc, the fiber Bragg grating (FBG) sensing technologies are regarded as a competent candidate for the long-term bridge health monitoring. According to the shifted Bragg wavelength of the light reflected by a fiber grating, the FBG sensors can accurately measure various physical properties such as strain, temperature, displacement, acceleration and corrosion. One special advantage of the FBG sensing technology is that only one demodulation device is required to acquire various physical properties simultaneously. Compared with the bridge health monitoring system using conventional sensors, this advantage makes the distributed sensing possible and data transmission more convenient because many FBG sensors can be series connected by a single fiber. In this paper, an integrated FBG sensing system is proposed for monitoring the static strain, dynamic strain, temperature and so on. For structural condition assessment, a data fusing technique is proposed to evaluate the health condition of the structure from the various physical signals measured from the system. Moreover, a trial sensing system is installed on a real bridge as a demonstration. The results of this study will supply a good guidance for the use of the FBG sensors on the health monitoring of real

bridges.

6174-98, Session 21

Wireless monitoring system using Bluetooth for crane

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Various monitoring sensors have been used for the monitoring and damage prediction of structures. Piezoelectric and optical fiber sensor that are required housing for the field applications are used widely. The impedance change of piezoelectric sensor is generally used for the damage prediction. However, the voltage change for the monitoring is not widely used. The direct current is used for the method of voltage while the alternating current is used for the method of impedance.

The inspection and monitoring for safety of crane is not easy because it is located in high level and the operation should be stop for the inspection. In this study, wireless monitoring system using various sensors and Bluetooth is developed. The sensors such as piezoelectric sensors, wire strain gages and load cells are applied for this system. A try for noise reduction in wires communication is suggested. This system is applied to the top crane to monitor the damage of main member.

6174-99, Session 21

Nanotechnology and MEMS-based systems for civil infrastructure safety and security: opportunities and challenges

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Critical civil infrastructure systems such as bridges, high rises, dams, nuclear power plants and pipelines present a major investment and the health of the United States' economy and the lifestyle of its citizens both depend on their safety and security. The challenge for engineers is to maintain the safety and security of these large structures in the face of terrorism threats, natural disasters and long-term deterioration, as well as to meet the demands of emergency response times. With the significant negative impact that these threats can have on the structural environment, health monitoring of civil infrastructure holds promise as a way to provide information for near real-time condition assessment of the structure's safety and security. This information can be used to assess the integrity of the structure for post-earthquake and terrorist attacks rescue and recovery, and to safely and rapidly remove the debris and to temporary shore specific structural elements. This information can also be used for identification of incipient damage in structures experiencing long-term deterioration. However, one of the major obstacles preventing sensor-based monitoring is the lack of reliable, easy-to-install, cost-effective and harsh environment resistant sensors that can be densely embedded into large-scale civil infrastructure systems. Nanotechnology and MEMS-based systems which have matured in recent years represent an innovative solution to current damage detection systems, leading to wireless, inexpensive, durable, compact, and high-density information collection. In this paper, ongoing research activities at AAMU Center for Transportation Infrastructure Safety and Security on the application of nanotechnology and MEMS to Civil Infrastructure for health monitoring will presented. To date, research showed that nanotechnology and MEMS-based systems can be used to wirelessly detect and monitor different damage mechanisms in concrete structures as well as monitor critical structures' stability during floods and barge impact. However, some technical issues that need to be addressed before full implementation of these new systems and will also be discussed in this paper.

6174-101, Session 21

A study on the application of CB-filled cement-based composite as a strain sensor for concrete structures

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Smart structural materials that can monitor stress and strain themselves have been more and more attractive in health monitoring for civil infrastructure due to their durability and promising performance in long-term service. This paper proposed the CB filled cement-based composite and studied its strain sensing properties, further more, the composite was used as a strain sensor to monitor the strain of concrete rectangular. The purpose of this study is to provide a practicable strain sensor material for long-term health monitoring for infrastructures.

Carbon black (CB) of 120nm in the amount 15% by weight of cement (i.e. 8.79% by volume of composite, respectively) was used, The cement used was Portland cement (P.O42.5) from Harbin Cement Company (Harbin, China). The water-cement ratio was 0.4. A water-reducing agent UNF (one kind of -naphthalene sulfonic acid and formaldehyde condensates) was used in the amount of 1.5% by weight of cement. The defoamer, tributyl phosphate (made in China), was used in the amount of 0.13 vol.% to decrease the amount of air bubbles. All the components were mixed in a mortar mixer and the mix was poured into oiled molds to form prisms of size 30Å~40Å~50mm for compressive testing.

DC electrical resistance measurement was made in the longitudinal axis, using the four-probe method, in which copper net served as electrical contacts. A FLUKE 8842A multimeter was used.

Compressive testing was performed on a 30Å~40mm side of each specimen. The strain was measured by using strain gages attached to the middle of the opposite sides of a specimen. The scheme of monotonically static loading up to specimen failure was arranged. During loading process, DC electrical resistance measurement was simultaneously made in the stress axis, using the four-probe method as described earlier. A linear relationship between the fractional change in resistivity and compressive strain was observed for cement-based composites filled with large content of CB, suggesting that this kind of composites was a promising candidate for strain sensor used in concrete structures. The straining sensing properties of the composites were affected by tunneling effect, interface between CB particles and cement matrix. Consequently, the effect of compressive strain on the resistivity of varied mixtures depended on which of these prevailing processes occurs when subjected to compressive strain.

The cement-based composite filled with CB was encapsulated with epoxide resin and put into the concrete rectangular with the size of 100Å~100Å~300mm. the concrete rectangular Compressive testing was performed on a 100Å~100mm side of each specimen. The strain was measured by using strain gages attached to the middle of the opposite sides of a specimen and the cement-based sensor simultaneously. The results indicated that cement-based composites filled with CB could be used as strain sensors for concrete structures.

6174-102, Session 22

Nondestructive sensing and stress-transferring evaluation of carbon nanotube, nanofiber, and Ni nanowire strands/polymer composites using an electro-micromechanical technique

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Nondestructive damage sensing and load transfer evaluation of carbon nanotube (CNT), nanofiber (CNF), and Ni nanowire strands/various polymer composites were investigated by electrical resistance measurement combined with micromechanical technique. Electrospun PVDF nanofiber was also prepared as a piezoelectric sensor. Electro-micromechanical techniques were to evaluate the sensing response of carbon nanocomposites by measuring electrical resistance under uniform cyclic loading. High volume% CNT composites showed significantly higher tensile properties than neat and low volume% CNT nanocomposites. CNF nanocomposites with smaller aspect ratio showed higher apparent modulus due to high volume content in case of shorter aspect ratio. CNT or Ni nanowire strands nanocomposites also showed humidity and temperature sensing within limited testing ranges. Thermally treated electrospun PVDF nanofiber showed higher mechanical properties than the untreated case due to the increase of crystallinity, whereas load sensing decreased in case of heat treated. In addition, electrospun PVDF nanofiber web responded the sensing effect on humidity and temperature as well. Nanocomposites using CNT, CNF, Ni nanowire strands, and electrospun PVDF nanofiber web can be nondestructively applicable practically for different multifunctional applications, respectively.

6174-103, Session 22

In-situ failure identification in woven composites throughout impact using embedded sensors

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Woven composites subjected to low velocity impact can fail due to simultaneous failure modes, such as matrix cracking, delamination, and fiber debonding and breakage. If woven composites are to be widely used within structural and mechanical elements, then the accurate identification and control of these failure modes is essential. In this study, measurements from low-impact velocity experiments and embedded and surface mounted optical fiber Bragg grating (FBG) sensors were used to obtain detailed information pertaining to damage progression in two-dimensional laminate woven composites. The woven composites were subjected to multiple strikes at 2m/s until perforation occurred, and the impactor position and acceleration were monitored throughout each event. From these mea-

surements, we obtained dissipated energies and contact forces. The FBG sensors were embedded and surface mounted at different critical locations near penetration-induced damaged regions. These FBG sensors were used to obtain initial residual strains and axial and transverse strains that correspond to matrix cracking and delamination. The transmission and the reflection spectra were continuously monitored throughout the loading cycles. They were used, in combination with the peak contact forces, to delineate repeatable sensor responses corresponding to material failure. From the FBG spectra, fiber and matrix damage were separated by an analysis based on signal intensity, the presence of cladding modes, and the behavior of individual Bragg peaks as a function of evolving and repeated impact loads. This provided an independent feedback on the integrity of the Bragg gratings. A comparison by number of impact strikes and dissipated energies corresponding to material perforation indicates that embedding these sensors did not affect the integrity of the woven systems and that these measurements can provide accurate failure strains.

6174-104, Session 22

Delamination prediction in composite laminates with piezoelectric sensor failure

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A selective number of strategically placed sensors are commonly designed in health monitoring structures. Typically, these sensors are used as active controllers, climate monitors, or damage detectors. Continuous monitoring of functioning sensors signal changes allow damage to be identified. However,errors introduced by faulty sensors can create erroneous conclusions regarding the health of the structure. The present work proposes an analytical method to monitor sensor signal changes incurred by the presence of delamination or faulty sensors. The proposed approach uses principle component statistical analysis to filter the characteristic of the sensor signals. The simulated signal processing is performed using a finite element procedure based on the refined layerwise theory, which is capable of modeling ply level stresses, and seeded delaminations are modeled with Heaviside step functions. A two-way electro-mechanical coupled field formulation is used to describe the piezoelectric sensor performance. The faulty sensors are modeled by decoupling the electro-mechanical fields in the stiffness matrix. The results obtained from simulations are verified through numerical simulations as well as with experimental results obtained using customized piezoelectric sensors and a Laser Scanning Vibrometer. The proposed approach is capable of identifying and filtering faulty sensor signals to detect discrete seeded delaminations in composite laminates.

6174-105, Session 23

Evaluation of attitude measurement using a color marker

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On-orbit assembling is a technology to construct a large structure such as a space reflector with a robot arm. The structure consists of a number of segments with a same shape and it is transported to an orbit in a state of segment. On orbit the structure is autonomously assembled with the robot arm, though a support from the ground can be provided at the critical stage. A color marker has been developed to help the robot with assembling, i.e., the robot can measure the position and attitude of a target segment by looking at a color marker attached onto each segment. The color marker consists of a square base plate painted black and a thin rod erected at the center of base plate. Three discs with different colors are printed on the surface of the marker. Two discs out of the three are located on the base plate and the other is on the top of the rod. In assembling operation the position and attitude of segment can be obtained from the positional relationship of those colored discs.

Therefore, it is of significance that each color discs are correctly extracted from an image captured with a camera on a robot. They can be extracted by a color image processing which leave only pixels that match a color table created previously. So, in a design of the marker the colors were carefully selected so as to be distributed as far away from each other as possible on the L*a*b* color coordinate system, which considerably contributed to the improvement of color disc extraction.

In order to make the attitude measurement with the color marker robust, it is necessary that the entire shape of the color discs are extracted under any lighting condition. We assume three different lighting sources available on orbit; the earth albedo, the direct sunlight, and a ring-shaped LED light mounted around a lens of camera. In laboratory experiment various kinds of performance of the marker necessary for on-orbit assembling have been evaluated so far. They include the measurement accuracy around three axes, the effect of defocused image, the robustness against different lighting sources, and the effect of interpolation method usually employed to convert a CCD array image to a normal color image, as well. From the result of the experiment it was shown that the color marker system can meet the accuracy requirement of the robot controller under orbital optical environment.

In 2007, an on-orbit demonstration of the color marker measurement system is scheduled to perform using a small satellite. The detail of the project will also be shown in our presentation.

6174-106, Session 23

Minimum rank perturbations for nonlinear parameter updating based on reduced order modeling

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Many structures have nonlinearities that play an important role in their dynamics. Often, these nonlinearities are neglected, and the system is modeled as being completely linear. This is motivated by the fact that linear analysis and damage detection methods are much more developed then their nonlinear counterparts. The first step in many damage detection algorithms is to perform frequency-domain or time-domain analyses to obtain properties of the system. The linear modal analysis field is very well developed and includes single input single output, single input multiple output and multiple input multiple output (MIMO) approaches. Each of these approaches have been developed for the time and frequency domains. The MIMO methods can also be divided into free and impulse response methods such as the poly-reference complex exponential method, eigensystem realization algorithm and Ibrahim time domain methods, and the forced response methods such as the auto-regressive moving average vector and direct system parameter identification, which use the forcing from natural excitations to determine the modal properties. The next step in several damage detection algorithms is to use the system properties to determine the damage location and extent. Again, the linear field is much more developed then its nonlinear counterpart, and includes sensitivity methods, eigenstructure assignment techniques, optimal matrix updates, and minimum rank perturbation methods. In this work, an algorithm for analyzing a nonlinear system as an augmented linear system is presented. This allows for the well developed areas of linear modal analysis and linear damage detection to be capitalized upon. The method uses a nonlinear discrete model of the system and the form of the nonlinearities to create an augmented linear model of the system. The key principle of the augmentation is its design such that the trajectory of the linear system (projected onto a lower dimensional subspace) is the same as the trajectory of the nonlinear system. A linear modal analysis technique that uses forcing that is known but not prescribed is then used to solve for the modal properties of the augmented linear system after the onset of damage. Due to the specialized form of the augmentation, the augmented system matrices may not be symmetric. Also, nonlinear damage causes asymmetrical damage in the updated matrices. Reduced order modeling is employed to obtain left eigenvectors of the system using the mass and stiffness orthogonality properties. A generalized minimum rank perturbation theory, which requires knowledge of both right and left eigenvectors, is developed to handle the asymmetrical damage scenarios. The damage extent algorithm becomes an iterative process when damage occurs simultaneously in the mass and stiffness matrices. The method is demonstrated using numerical data from a nonlinear 3-bay truss structure. Various damage scenarios of the nonlinear system are used to demonstrate the effectiveness of the augmentation coupled with reduced order modeling and generalized minimum rank perturbation theory, and the effect of random noise on the technique. The nonlinearities explored include cubic springs and Coulomb friction.

6174-107, Session 23

Finite element modeling and simulation of piezoelectric wafer active sensors interaction with the host structure for structural health monitoring

W. Liu, V. Giurgiutiu, Univ. of South Carolina

Crack detection with piezoelectric wafer active sensors (PWAS) is emerging as an effective and powerful technique in structural health monitoring (SHM). Modeling and simulation of PWAS and host structure play an important role in the SHM applications with PWAS. For decades finite element method has been extensively applied in the analysis of piezoelectric materials and structures. The advantage of finite element analysis over analytical solutions is that stress and electrical field measurements of complex geometries, and their variations throughout the device, are more readily calculated. FE allows calculation of the stress and electric field distributions under static loads and under any applied electrical frequency, and so the effect of device geometry can be assessed and optimized without the need to manufacture and test numerous devices. With powerful commercial FE codes coupled-fields analysis- mechanical, electrical, circuits and acoustics analysis should all be integrated together to provide a systemic overview of the piezo-

electric sensors/actuators (even arrays of them) and the host structures.

Electro-mechanical (E/M) impedance technique utilizes the direct and the converse electro-mechanical properties of piezoelectric materials, allowing for the simultaneous actuation and sensing of the structural response. In this paper simple case of 1-D beam with piezoelectric active wafer (PWAS) sensors is first investigated and the structural E/M impedance was calculated based on the simulation result. The simulated E/M impedance spectrum was then compared to analytical calculation and the experimental data acquired with impedance analyzer. Coupled-field analysis is also performed on square PWAS using elements with voltage degree of freedom. The comparison of vibration mode shapes and calculated E/M impedance to experimental data are then provided.

6174-108, Session 23

Design and fabrication of a piezoelectric instrumented suspension for hard disk drives

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As data densities in computer hard disk drives increase, airflow-induced vibration of the disk drive suspension becomes a major barrier to positioning the read-write head with sufficient precision. One necessary component for reducing these vibrations is a dedicated sensor system for detecting vibration on the sensor arm directly, which enables high-frequency sampling and modal selectivity. In this paper, an efficient method for identifying optimal position and shape of piezoelectric strain gages on a flexible structure is presented, and applied to the steel suspension of a hard disk drive. Zinc oxide deposition processes are adapted to steel substrates, and used to fabricate miniature zinc oxide strain gages at the optimal strain gage location. Substrates with sensors installed were assembled into full disk drive suspensions and tested in a commercial disk drive. Sensor resolution to 500 nanostrain is demonstrated on simple cantilevers, and several vibration modes are detected simultaneously on prototype instrumented suspensions.

6174-109, Session 23

Continuous health monitoring of the thermal protection system for future spacecraft

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The thermal protection system (TPS) represents the greatest risk factor after propulsion for any transatmospheric mission (Dr. Charles Smith, NASA ARC). Any damage to the TPS leaves the space vehicle vulnerable and could result in the loss of human life as what happened in the Columbia accident. Aboard the current Space Shuttle Orbiters no system exists to notify the astronauts or ground control if the thermal protection system has been damaged. The goal of this project is to add self-diagnostic capability to future spacecrafts through the use of a fiber-optic network embedded in the TPS. This system of sensors would allow for the detection of tile fracture, optical temperature measurement at different depths within the tile, communication with neighboring tiles, and detection of communication loss.

The hardware that would be added to each tile consists of a radiation-hardened microcontroller, fiber-optic sensors and power. Each tile would have the ability of reporting its own damage as well as reporting a loss of communication with any of its neighboring tiles. Such a network would provide continuous health monitoring of the TPS in real-time. “Intelligent Tile” technologies are readily adaptable to both tile-based and monolithic ablative thermal protective systems.

6174-110, Session 24

Developing thermal energy computing tools for sonic infrared imaging

X. Han, Wayne State Univ.

Sonic IR Imaging is a novel NDE technique, which combines a short ultrasonic pulse excitation and Infrared Imaging to detect defects in materials and structures. The ultrasound pulse, typically a fraction of a second, causes heating in the defects, which results in the change of IR radiation from the target. This change can be detected by infrared sensors, thus, defects can be identified. One key objective in developing this technology is to optimize the IR signal with minimum ultrasound excitation energy being applied to the target. From our work, we learned that the ultrasonic frequency, coupling medium between the ultrasonic transducer and the target, the pressure from the transducer to the target, the characteristics of the target itself, etc. are all factors that affect the IR signals. Of course, different IR sensors have different response for the same IR radiation. In this paper, we’ll describe the thermal energy computing tools developed for analyzing data from different sets of parameters in Sonic IR Imaging.

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6174-111, Session 24

An application of smart dust for pavement condition monitoring

N. A. Ferzli, C. J. Sandburg, T. King, J. Pei, M. M. Zaman, H. H. Refai, Univ. of Oklahoma

Pavement maintenance is vital for travel safety; detecting road weather conditions using a wireless sensing network poses many challenges due to the harsh environment. This paper presents some preliminary results of an ongoing effort of applying “Smart Dust” sensor network for monitoring pavement temperature and moisture condition to detect icy road condition. Careful considerations yield effective solutions to various hardware and software development issues including the selection of sensors and antenna, design of casing, interfacing motes with alien sensors and programming of motes. The performance of motes in extreme temperature and humidity conditions are examined based on environmental chamber testing. In addition, a series of experiments is carried out to study traffic interference to packet delivery performance of a small-scale sensor network in a pseudo-field environment; the results are analyzed and challenges are identified in this smart sensing application. All these research activities would benefit robust real-world implementations of off-the-shelf sensor network products.

6174-112, Session 24

The feasibility analysis of monitoring falling stones by means of an optical interferometer

Y. Lin, M. Chen, National Sun Yat-Sen Univ. (Taiwan); W. Lin, Ta Jen Univ. (Taiwan)

The geologic age of Taiwan is too young to have solid rocks. Suffering from the debris flow induced by the earthquakes and many flood disasters in recent years, the geology even shows the flimsiness. It is very frequent to find lots of falling stones on the highway; sometimes disasters take place. The optical fiber has the features of low loss and wide bandwidth; it has replaced the coaxial cable as the mainstream of the communication system in recent years. Because of high sensitivity characteristic, the interferometer is usually applied to long distance weak signal detection. In general, the highway with potentially falling stone dangerous area usually located in the far away mountain area, the electric power supply is very difficult, also the weak signal makes it uneasy to monitor. Hence, the object of this paper is to study the feasibility of a monitoring system, which can match the existed optical fiber communication and a high sensitivity interferometer as a falling stone monitoring system.

6174-113, Session 24

Polymer optical fiber sensors for the civil infrastructure

S. Kiesel, P. Van Vickle, K. J. Peters, T. Hassan, M. Kowalsky, North Carolina State Univ.

Given that the engineering community is firmly entrenched in the ‘Performance-Based Era’, it is essential that the tools that engineers use for assessment, analysis, and design should be able to capture both “local” and “global” responses of structures under dynamic load conditions. In order to truly understand the failure mechanisms of structures, it will be essential to have reliable sensors that can measure large strains at high strain rates. Such a sensor would have significant immediate implications for structural testing and monitoring as researchers would gain previously unavailable insight into the localized failure mechanisms due to inelastic deformation and damage accumulation.

This article presents current research at NCSU investigating the use of polymer fiber sensors for the performance-based assessment and health monitoring of civil infrastructure systems. Although the sensor described could be utilized to measure strains under a variety of load conditions and structural materials, this research program focuses on its application to concrete and steel structures subjected to dynamic load conditions, such as those imposed due to earthquakes loads. For this reason, an interferometric sensor is developed. The mechanism for embedding the gages in concrete and placing them on the surface of steel is investigated and, afterwards, is applied to large scale structural systems in attempt to demonstrate their potential by seeking out previously unavailable data in structural members. However, the use of the POF at large strain rates is not without significant challenges as compared to previous small deformation optical fiber sensors. This article also presents the implications of the large deformations on

the opto-mechanical response of the sensors, as well as the data acquisition method to be utilized for the new sensors.

6174-114, Session 24

Application of FBG sensors in roller compacted artificial concrete dam model

L. Ren, H. Li, Sr., X. Lian-Qin, Dalian Univ. of Technology (China)

Optical fiber sensors have received increasing attention in the fields of civil engineering for their superior ability of explosion proof, immunity to electromagnetic interference and high accuracy, especially fitting for measurement applications in harsh environment. In this paper, a novel FBG (fiber Bragg grating) strain sensor, which was packaged in a 1.2mm stainless steel tube by epoxy resin, was developed. Strain transferring characteristics was conducted in the calibration experiment on the plain concrete beam using universal testing machine. Three tube-packaged strain FBG sensors were applied in the vibration experiment of roller compacted artificial concrete dam model. The strain analysis was done with different work conditions by three dynamic load of noise, sine wave and random wave. The different parts of roller compacted mimic concrete dams were monitored successfully in elastic strain and split strain by action of dynamic load. The results show that possible fatigue and breakage damages can be monitored conveniently by embedded FBG sensors, and information can be well provided for structure health diagnoses under the action of dynamic load.

6174-115, Session 24

Dynamic displacement measurement

J. J. Lee, Y. Fukuda, M. Shinozuka, Univ. of California/Irvine

Highly cost-effective real-time visualization of dynamic displacement is made possible by means of a device integrating a telescope, camcoder and laptop with efficient software. The resolution can be made in the range of 0.2 mm at 0-20 Hz from 100 m distance. At this time, we plan to use this telescopic image processing system for the Vincent Thomas bridge, a Caltrans major suspension bridge in Long Beach, CA, servicing a major conduit for transportation of cargos in and out of the Port of Los Angeles and Long Beach.

6174-116, Session 25

Self-powered sensory nerve system for civil structures using hybrid Forisome actuators

R. A. Shoureshi, Univ. of Denver

In order to provide a true distributed sensor and control system for civil structures, we have developed a Structural Nervous System that mimics key attributes of a human nervous system. This nervous system is made up of building blocks that are designed based on mechanoreceptors as a fundamentally new approach for the development of a structural health monitoring and diagnostic system that utilizes the recently discovered plant-protein forisomes, a novel non-living biological material capable of sensing and actuation. In particular, our research has been focused on producing a sensory nervous system for civil structures by using forisomes as the mechanoreceptors, nerve fibers, neuronal pools, and spinocervical tract to the nodal and central processing units.

This paper will present up to date results of our research, including the design and analysis of the structural nervous system.

6174-117, Session 25

Fiber-reinforced composites for structural health monitoring

H. Kumagai, Shimizu Corp. (Japan); H. Inada, Y. Inada, Ohsaki Research Institute (Japan); Y. Okuhara, H. Matsubara, Japan Fine Ceramics Ctr. (Japan)

This research has been conducted as a part of the “Advancement of Basic Technological Research” project (2001-2005) supported by New Energy and Industrial Technology Development Organization, Japan. In this research project, we have developed electrically conductive fiber reinforced composites for structural health monitoring.

Recently concrete structures with fiber reinforced polymer is becoming widely used and its design and construction methods have been confirmed. This research is aimed at structural health monitoring system in concrete structures through the use of electrically conductive fiber reinforced composites which can memorize maximum strain experienced. This system that would observe change of electrical resistance in the material to identify damages is cost effective since no advanced instrumentation is needed.

The carbon particles with a mean diameter of 50nm are dispersed in epoxy resin to form a conductive part. Surrounding it, the glass fiber filaments are incorporated in the mixture as an insulating part. In the conductive part, the carbon particles form a continuous link (percolation structure) with each other to make a conductive path. Applying tensile strain to the material interrupts the conductive path and increases the electrical resistance. Because disconnected contacts between the particles are not restored even after unloading, the material generally keeps the resistance value corresponding to the maximum strain experienced until the applied strain exceeds the original peak value. This composite can be shaped into two types. One type has an appearance like a rod, which is embedded into the structures prior to the casting of concrete. Another is a flat bar type, which is utilized to be bonded on the surface of concrete.

Effectiveness and sensitivity of these developed materials were experimentally confirmed using slab, column and frame specimens. These loading test results are summarized in this paper.

6174-118, Session 25

FRP confined smart concrete/mortar

Y. Xiao, Univ. of Southern California

Smart concrete and smart cement mortar with self-sensing capability based on electrical conductive admixtures have been recently investigated by several researchers. In current study, FRP confined smart concrete/mortar sensors were invented with drastically improved measurement range. Several trial mixes were made using cement mortar and nano to micron-scale graphite powders at different mix proportions. Compression tests were conducted on smart mortar cylinder specimens with or without FRP confinement. Two-probe method was used to instrument the electrical resistance of the smart cement mortar specimens before and during the compression tests. Strong correlation was recognized between the stress and electrical resistance of the smart mortar. Most important, the test results indicated that the FRP confinement can significantly enlarge the range of such self-sensing property.

This paper introduces the details of the invention of the confined smart concrete/mortar and the experimental testing results. Mechanical behaviors of the FRP confined smart mortar specimens were discussed in details along with the instrumentation results of the electrical resistance. Attempt was also made to understand the micro structures of the smart mortar with electron microscope imaging.

6174-119, Session 26

Effect of temperature on modal variability for a curved concrete bridge

C. Liu, J. T. DeWolf, Univ. of Connecticut

The University Of Connecticut, with support and assistance from the Connecticut Department of Transportation, has been involved in monitoring bridges in the State since the1980s. These studies have provided information on how different bridges behave, have been used to develop monitoring techniques, both experimental and analytical, and have provided guidance on renovations in order to assist the State in the management of its bridge infrastructures. Currently a network of five bridges in the State is being monitored using remote monitoring systems operated by researchers at the University.

This paper presents the results of a study to determine the effect of temperature on modal variability for one of the bridges in this study. The bridge is a curved post-tensioned box girder bridge with three continuous spans. The monitoring system was installed in May, 1999, and has been operating since then. The system has of 16 accelerometers, 12 thermocouples and 6 tiltmeters. The tilt and temperature data are collected at fifteen minute intervals. The data for the accelerometers is saved when large vehicles cross the bridge using a trigger approach. Each large vehicle produces a 30 second record Data is then transmitted to the University of Connecticut for further processing. The acceleration data is converted to frequency domain by Fast Fourier Transform for extraction of the modal information.

When applying ambient vibration based health monitoring techniques to any real structure, it is not only the structural health that influences the modal characteristics, but also changes in temperature can be an important factor. There is concern that changes due to temperature variations may mask changes due to structural damage. A thorough understanding of this uncertainty is necessary so that changes in vibration response resulting from damage can be discriminated from changes that are due to temperature variability.

This paper presents the results of a study to evaluate the ambient vibration information over a full year period in which data was collected continuously. The effects of temperature change on the bridge’s modal frequencies are analyzed and

interpreted. This correlation between the natural frequencies and temperature is essential to establishing a structural health monitoring approach that can provide for indications that damage has occurred.

6174-120, Session 26

Identification of modal responses of hysteretic structures using Hilbert-Huang method

C. Poon, C. Chang, The Hong Kong Univ. of Science and Technology (Hong Kong China)

Hilbert-Huang method is proposed to identify of modal responses of hysteretic multi-degree-of-freedom (MDOF) structures under free vibration. In this study, a response time history is first decomposed into intrinsic mode functions (IMFs) using the empirical mode decomposition (EMD) method. Then, the Hilbert transform is applied to each IMF to obtain the instantaneous amplitude and frequency. The Kryloff-Bogoliuboff method of averaging, which analytically determines an approximate relationship between the vibration amplitude and frequency of lightly nonlinear single-degree-of freedom (SDOF) systems, is extended to obtain the amplitude-frequency relationships of the modal responses of lightly nonlinear MDOF systems. In the modified averaging method, the number of major components, known as modal responses, found from the response is assumed to be the same as the degree of freedom of the system. It is shown that the amplitude-frequency relationships of the IMFs obtained from the Hilbert-Huang method agree quite well with those of the modal responses obtained from the modified averaging method. The applications of the proposed method are illustrated using two examples with different dynamic characteristics. A two-degree-of-freedom building model with nonlinear elastic stiffness is used in the first example to show the applicability of the modified averaging method to the nonlinear MDOF structures. In the second example, the Bouc-Wen model is used to simulate the hysteretic behavior of the building model. Numerical simulation results demonstrate that the proposed method can identify the modal responses. The results suggest that the IMFs can be used to determine the physical dynamic properties of hysteretic structures.

6174-121, Session 26

Linear and nonlinear structural identifications using the support vector regression

J. Zhang, Kyoto Univ. (Japan); T. Sato, Kyoto Univ. (Japan) and Waseda Univ. (Japan)

Robust and efficient identification methods are necessary to study in the structural health monitoring field, especially when the I/O data are accompanied by high-level noise and the structure studied is a large-scale one. The Support vector Regression (SVR) is a promising nonlinear modeling method that has been found working very well in many fields, and has a powerful potential to be applied in system identifications. The SVR-based methods are provided in this article to make linear large-scale structural identification and nonlinear hysteretic structural identifications.

The LS estimator is a cornerstone of statistics but less robust to outliers. Instead of the classical Gaussian loss function without regularization used in the LS method, a novel e-insensitive loss function is employed in the SVR. Meanwhile, the SVR adopts the “max-margined” idea to search for an optimum hyper-plane separating the training data into two subsets by maximizing the margin between them. Therefore, the SVR-based structural identification approach is robust and accuracy even though the observation data involve different kinds and high-level noise.

By means of the local strategy, the linear large-scale structural identification approach based on the SVR is first investigated. The novel SVR can identify structural parameters directly by writing structural observation equations in linear equations with respect to unknown structural parameters. Furthermore, the substrutural idea employed reduces the number of unknown parameters seriously to guarantee the SVR work in a low dimension and to focus the identification on a local arbitrary subsystem.

It is crucial to make nonlinear structural identification also, because structures exhibit highly nonlinear characters under severe loads such as strong seismic excitations. The Bouc-Wen model is often utilized to describe structural nonlinear properties, the power parameter of the model however is often assumed as known even though it is unknown in the real world. In the case of unknown-power parameter, the nonlinear structural identification problem is more intricate and few approaches are dedicated to this problem. In this article, a model selection strategy is proposed to determine the unknown power parameter of the Bouc-Wen model. Meanwhile, the optimum SVR parameters are automatically selected instead of tuning manually. Based on the produced power parameter and optimum SVR parameters, the SVR is executed to identify nonlinear hysteretic structural parameters accurately and robustly.

The numerical examples for a linear large-scale structure and a five-DOF nonlinear hysteretic structure provided illustrates that the proposed technique has excellent performance in robustness and accuracy for linear and nonlinear structural identifications, even when the noise exits in I/O measurements is high-level and non-Gaussion. Moreover, an incremental training algorithm utilized to solve SVR formulation in a sequential way not only significantly reduces the computation time, but also makes the structural health monitoring on-line.

6174-122, Session 26

Vibration sensor data compression and its effect on structural system identification

Y. Zhang, J. Li, Lehigh Univ.

This paper deals with sensor data compression algorithms for efficient storage, transmission and retrieval of structural vibration response data and the effects of lossy data compression on vibration-based structural system identification. Structural health monitoring systems installed in civil and mechanical structural systems provide vibration response data which provide input data to the quantitative study of structural behaviors. Current trend in structural health monitoring is towards the use of a substantial number of sensors for improved accuracy. Sensor network consisting of hundreds to several thousands of sensor nodes is envisioned to be widely used in future smart structural systems. In order to facilitate efficient data transfer, retrieval and storage of vibration sensor data, innovative sensor data compression techniques are highly desired since a very high data rate is anticipated when large scale sensor networks are used. This paper first presents an overview of vibration sensor data compression techniques currently under development at Lehigh University, which include linear predictor-based sensor data compression algorithm and wavelet-based sensor data compression algorithm. The linear predictor-based sensor data compression can be derived from sensor network data and measured input signals. A vibration sensor data compression algorithm that can utilize structural system information made available from sensor network data for maximized data compression performance is also presented in this paper. Finally, the effects of lossy data compression in which information loss occurs due to the use of quantizer are presented. Real data collected from building and bridge structures are used in this study.

6174-123, Session 26

Experimental study of a PEM-based second order structural system identification technique

J. Li, Y. Zhang, Lehigh Univ.

This paper deals with a prediction error method (PEM)-based structural identification algorithms which can identify second order structural parameters of linear structural dynamic systems directly from measured vibration data. The state space model for linear structures is first expanded into linear ARMAX or ARMA models by Matrix Fraction Descriptions (MFD). PEM is then applied to estimate the second order structural parameters directly from measured time domain data. To avoid the commonly encountered difficulties associated with input measurement, a two-stage structural identification procedure is proposed. Once the mass matrix is identified from the first stage, data collected from ambient vibration survey can be used to identify the remaining structural parameters in the second stage.

Advantages of the proposed structural identification method can be summarized as follows: (i) it provides an automated procedure which eliminates the need for trial-and-error updating of structural parameters to match the observed response; (ii) once the structural mass is known, the proposed structural identification method can be applied to ambient vibration applications without the need for measuring the input forces; (iii) it can incorporate as much as possible structural information known a priori such as stiffness of some structural elements into the structural parameter identification process and thus improves the identification efficiency and accuracy; (iv) furthermore, unlike other second order parameter identification algorithms, the proposed method does not need to identify modal properties first.

The proposed structural identification method has an important use in structural health monitoring since damage can be reflected by the changes in stiffness or damping coefficients of the structure. The effectiveness of the proposed structural identification method as well as the corresponding two-stage structural health monitoring method is experimentally evaluated at Lehigh University’s Smart Sensing Technology test-bed, which consists of a reconfigurable truss structure. The results show that the proposed method is capable of locating and quantifying damages reasonably well in the presence of measurement noises and limited sensor information.

6174-124, Session 27

Multiple piezoceramic transducers (PZT)-structure interaction model

V. G. Annamdas, C. K. Soh, Nanyang Technological Univ. (Singapore)

Piezoceramic (PZT) transducers are extensively used for damage detection in electromechanical impedance (EMI) based structural health monitoring (SHM) of aerospace, civil and mechanical (ACM) systems. In the EMI models, the PZT transducers are generally surface bonded to the host structure and then subjected to actuation, so as to interrogate the structure for the desired frequency range. The interrogation results in the prediction of electro-mechanical admittance signatures, which is the inverse of mechanical impedance of the structure. These signatures work as indicator to predict the health/integrity of the structure as any change in these signatures during the life of the structure is indication of crack or damage or failure in the structure. The existing PZT-structure interaction models consider the PZT to be negligible in mass and thus ignored. However, for multiple PZT-structure interaction, influence of the PZT mass becomes significant as there is significant increase in the number of PZT transducers used.

This paper presents a novel semi-analytical multiple PZT-structure interaction model which considers the mass influence of the multiple PZT transducers. The model involves numerical modelling, modal analysis and analytical formulation of admittance signature, and thus, is semi-analytical in nature. The numerical analysis is to obtain the structure response for use as input to the analytical equations, so as to finally predict the admittance signature. In the model, the host structure is discretized into finite elements, and the elements beneath the PZT transducers are identified as the adaptable elements for transfer of the mass of the PZT transducers. The total mass of all the multiple PZT transducers are then distributed to the adaptable elements. The model is able to simulate the interaction between multiple rectangular PZT transducers and their host structure without restricting to square shaped and electrically isotropic PZT transducers, and hence, is generic in nature. The derived model is then experimentally verified using lab sized aluminium plate. For the verification, equal numbers of square and rectangular PZT transducers are surface bonded on an aluminium plate. The impedance analyzer via multiplexer box set-up is used to obtain the admittance signature. The obtained experimental signatures are then compared to the predicted admittance signatures.

In addition to deriving the new model, the present research provides extensive understanding about distributed and multiplexed transducers using mode shape analysis. The derived multiple PZT-structure interaction based semi-analytical EMI model is simple, reliable and generic in nature; and is hence expected to be applicable for the non destructive evaluation (NDE) of most ACM systems.

6174-125, Session 27

Effect of SMA bars on cyclic behaviour of low-rise shear walls

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Past RC panel tests performed at the University of Houston show that reinforced concrete membrane elements under reversed cyclic loading have much greater ductility when steel bars are provided in the direction of principal tensile stress. In order to improve the ductility of low-rise shear walls under earthquake loading, high seismic performance shear walls have been proposed to have steel bars in the same direction as the tensile principal direction of applied stresses in the critical region of shear walls. This paper presents the results of reversed cyclic tests on three low-rise shear walls with SMA bars. The height, width, and thickness of the designed shear walls are 1.0 m, 2.0 m, and 0.12 m, respectively. SMA bars are provided in the directions of 27 degrees to the horizontal that are in the diagonal direction. The reinforcing bars of the shear walls are in vertical and horizontal directions. The ratios of both SMA and reinforcing bars are 0.24%. The main parameter used in the study is the type of SMA bar, namely Superelastic and Martensite SMA bars. The test results from the walls with SMA bars are also compared to a conventional wall without SMA bars. Test results also show that the maximum shear strengths of the tested walls are affected by the SMA bars. It was found that the shear wall with Martensite SMA bars has greater residual displacement. In contrast, the shear wall with superelastic SMA bars has less residual displacement. At the ultimate state, one of the four superelastic SMA bars buckled, resulting in less energy dissipation capacity than the expected value. Preventing buckling of SMA bars is the research focus in the near future.

6174-126, Session 27

Interface transferring mechanism and error modification of FRP-OFBG strain sensor based on standard linear viscoelastic model

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This paper presents the interface transferring mechanism and error modification of the Fiber Reinforced Polymer-Optical Fiber Bragg Grating (FRP-OFBG) sensing tendons, which including GFRP- (Glass Fiber Reinforced Polymer) and CFRP- (Carbon Fiber Reinforced Polymer) OFBG, using standard linear viscoelastic model. The optical fiber is made up of glass, quartz or plastic, et al, which creep strain are very small at room temperature. So the tensile creep compliance of optical fiber is independent of time at room temperature. On the other hand, the FRP (GFRP or CFRP) is composed of a polymeric matrix, for example epoxy resins, with glass or carbon fibers, which shear creep strains are dependent of time at room temperature. Hence, the standard linear viscoelastic model is employed to describe the shear creep compliance of FRP along the fiber direction. The expression of interface strain transferring mechanism of FRP-OFBG sensors is derived based on linear viscoelastic theory. The effects of FRP viscoelasticity on the error rate of FRP-OFBG sensing tendons are included in the above expression. And the transient and steady-state error modified coefficient of FRP-OFBG sensors is obtained using initial value and final value theorems. The theoretical prediction coincides with experimental results.

6174-127, Session 27

Structural configuration and analysis of Kiewitt single layer CFRP reticulated dome

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As increased in span, the selfweight and internal force of space structures in large span are also much increased, thus span of space structures is limited. Compared to conventional materials, advanced composites have many potential advantages, such as high specific stiffness and strength, good corrosion resistance and thermal insulation. Furthermore, components made of these composites achieve a weight saving of about 20% when compared with conventional construction materials made of light metals. The off-axis piles in multi-layered pipe can be used to match potential loading directions so as to offer optimal design of various structural components. Aim at different applications, researchers have studied their mechanical properties and failures, including bending, transverse loading, axial compression and internal pressure loading conditions. These studies provide an good foundation for the application of Filament-wound (FW) composite material in civil engineering structures.This paper describes structural configuration of Kiewitt single layer CFRP reticulated domes, and gives the design procedure of FW CFRP pipes subjected to axial loading in CFRP reticulated domes. Based on the procedure, compressive strength and buckling critical load for CFRP pipes varied winding angles from 00 to 900 was provided. Stability analyses for CFRP reticulated domes were carried out using the general purpose finite element program ABAQUS. By complete load-deflection response analysis, the load-deflection responses and the buckling modes of reticulated domes made up of members with different winding angles were given, and compared with steel reticulated dome, CFRP reticulated domes display very advanced behaviors in selfweight, stiffness, structural deflection.

6174-128, Session 27

Modeling job sites in real time to improve safety during equipment operation

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The high incidence of fatalities resulting from operation of heavy equipment in maintenance and construction operations in infrastructure systems is of major concern to the construction industry. One of the major causes of fatalities is the lack of safety features installed on the heavy equipment that is currently in use. Therefore, increase safety of equipment operation is one of the ultimate goals in infrastructure operations. Tele-operated systems, which combine remote control by a human operator with the desirable features afforded by an “intelligent” machine, have gained wide acceptance as an alternative to traditional methods of control. These systems contain a significant human component, as they ultimately depend on the intuitive ability of humans for proper control of the manipulators. However, the safety of the operation cannot be guaranteed, since various dynamic environmental factors typical of construction sites, such as noise, precipitation, dust, and limited visibility, combined with constant changes of building units, target materials, and equipment position, may confuse the operator.

Real-time local scene modeling may help in tele-operation, since it provides the ability to quickly extract the most pertinent information in the work space. Current methods for construction site modeling employ large, expensive range scanners that produce dense point clouds that require hours or even days of both skilled manual and automatic segmentation to arrive at a finished model. While these methods produce very detailed models of the scanned scene, useful for obtaining as-built drawings of existing structures, the associated computational time burden precludes the methods from being used on site for real-time decision-making. The dynamic nature of a construction site requires modeling times on the order of seconds. Moreover, in applications such as obstacle avoidance, highly accurate and detailed models of objects are not needed. Experimental results from earlier research conducted by the authors indicated that models of " target" objects and "clusters of objects" to be avoided can be created rapidly and with sufficient accuracy for obstacle avoidance and automation functions from a limited number of sense data (sparse point clouds) with the aid of human intelligence. These methods provided a foundation for an on-going study that is addressing complex real site situations, including dynamic information (motion of personnel and equipment).

This paper describes a current research that aims to refine and expand the previously developed building blocks (geometrical primitives, convex hull etc.), by developing more general methods of handling on-site spatial information including the development of methods, algorithms, and spatial syntax principles pertinent to site characteristics and methods for integrating the motion of objects or people into the site model. On-site spatial information would also allow for a thorough site analysis that may be used for rapid site layout analysis, identification of safety zones, creation of as-builts, etc The researchers are also developing an obstacle avoidance system for equipment control that uses the rapidly generated site models. Preliminary results, including algorithms and experiments are presented.

6174-129, Session 27

Updating finite element model of structures with semi-rigid joints and boundary

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A good finite element model to accurately predict the dynamic response of an actual structure has been a prerequisite for many damage detection techniques. Model updating is to make use of experiment data to update an analytical finite element model to produce analytical model which is consistent with the actual structure.

Idealization and uncertainties that deviate the analytical models to actual structures include material property, structural geometry, boundary condition, joint rigidity, and discretization of continuum, etc. In finite element modeling of structures, joints are either taken as perfectly pinned joints or fully rigid joints. In this paper, the effect of semi-rigidity of joint and boundary on structural response, and updating the structures with semirigid joints and boundary are studied. A hybrid finite element that consists of a beam element with two semirigid connections at its ends is introduced. Finite element model with hybrid elements is assembled. An improved inverse eigensensitivity method with Genetic Algorithm is proposed to update structures with semirigid joints. The method proposed is experimentally studied by update a 14-bay beam. The results show that the method can produce an analytical model that better duplicates the dynamic property of actual structure while keep physical connectivity between them.

Conference 6175: Testing, Reliability, and Application of Micro- and Nano-Material Systems IV

Wednesday-Thursday 1-2 March 2006

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6175-19, Poster Session

Real-time microcomputed tomography

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The development and use of micro- and nanofabricated assemblies yields a growing number of industrial applications worldwide. Driving industrial sectors are at first the assembly in electronics with its demands for higher packing density, but also the automotive industry aiming to reduce CO<sub\>2</sub\>/NO<sub\>x</sub\> emission by improved combustion management using micro structured nozzles. However, characterization and quality control are becoming more and more complicated because of the shrinking dimensions of the parts themselves, on the one hand, and since features can't be accessed from outside. That's why 3D-methods will become more important to reveal those hidden structures. Usually, these methods require long data acquisition times and a horrendous amount of computer memory. Nowadays, the computer memory is not a major problem anymore. But the calculation is still difficult and time consuming. In the past decade the X-ray division at Fraunhofer IZFP had performed comprehensive works to improve the algorithms in order to meet real-time requirements when calculations are part of in-line controlling systems to be inserted into production lines. Selected examples will describe ongoing activities at Fraunhofer IZFP in the field of real-time Micro-3D Computed X-ray Tomography. Limitations and potentials of the method will be discussed.

6175-20, Poster Session

Acoustic and ultrasonic scanning probe microscopy utilizing integrated-actuator cantilevers

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Conventional AFM technologies employ a rectangular or triangular cantilevered, micromachined tip to characterize the surface topography of a sample. A laser reflected from the backside of the cantilever onto a position-sensitive photodetector is used to measure vertical (or torsional) cantilever displacement resulting from the interaction of the tip with the sample surface. External piezoelectric transducers are used to control the sample height relative to the cantilevered tip and either raster-scan the tip over the sample surface or scan the sample surface under a laterally immobile tip. There is a wide array of dynamic AFM approaches wherein a separate piezoelectric transducer is also used to vibrate the tip at or near a resonance frequency of the cantilevered support beam to increase the sensitivity of the tip to surface electrostatic or Van der Waals forces. Cantilevers with integrated displacement sensors2, integrated actuators, or both have been developed to allow faster, simpler or parallel operation of the AFM. This approach is particularly attractive for adaptations of AFM to so-called ultrasonic or acoustic atomic force microscopy, referred to as UFM and AAFM, respectively.

Recently, the fabrication of cantilevers integrated with actuation and sensing components has opened avenues for feedback-based driving of micromachined cantilevers at higher-order resonance frequencies while sensing average deflection without the need for an optical deflection pathway for average deflection sensing. The work presented here will review recent efforts by our group in fabricating micromachined cantilevers with integrated piezoresistive deflection-sensing components combined with integrated ZnO actuation layers to induce cantilever deflection and incorporating this cantilevers in SPM-based acoustic or ultrasonic imaging systems. The first and second-pass fabrication results will be reviewed regarding cantilever release and ZnO actuator (and electrode) fabrication. Dynamic response data from these structures, measured via laser Doppler vibrometery reveal the expected resonance structure for a cantilever of these dimensions. Utilization of these cantilevers in acoustic-based scanning probe systems including ultrasonic force microscopy (UFM) and acoustic AFM will be presented. Preliminary investigations show that 'on-board' actuation yields mechanical image contrast as expected for these SPM imaging modes.

6175-21, Poster Session

STEAM: a software tool based on empirical analysis for micro electro mechanical systems

A. Devasia, A. Pasupuleti, F. Sahin, Rochester Institute of Technology

Recent emphasis in the field of MEMS was on the development of computer aided design (CAD) tools for MEMS structures [1]. This is because MEMS devices demand a set of complex design requirements such as low power consumption, small size and weight. Due to the limitations of the current day technologies, these requirements are often met by physical prototyping that is expensive and time consuming [2]. These software tools when sufficiently precise and computationally effective can have commercial advantageous in shortening the design cycle and as a result they could prove to be cost effective. However, MEMS design is still at its infancy due to the lack of proper mechanical properties of thin films. In MEMS, thin films are often used as basic structural building block. Existing software tools utilize bulk values for material properties. In literature it was reported that such an assumption could result in inaccurate behavior predication [3-6]. As a result, understanding their mechanical properties is considered to be necessary and important for the long-term reliability and for the improvement in the performance of various MEMS devices.

This research proposes a new methodology for estimating the material properties as well as mechanical behavior of thin films that are utilized in MEMS devices. A simulation engine that is based on empirical analysis was developed for modeling the material properties of MEMS structures. The proposed methodology emphasizes on the empirical estimation techniques to generate useful material properties at the microscopic level, thereby accelerating the MEMS design process [7]. A literature review was performed to understand the physical phenomena that govern the mechanical behavior of thin films materials. This survey indicated that the present day models operate under a wide range of assumptions that may not be applicable to the micro-world. Thus, this methodology is foreseen to be an essential tool for MEMS designers as it would relate the loading parameters, material properties, and the geometry of the microstructures with its performance characteristics. The process involves learning the relationship between the above parameters using non-parametric learning algorithms such as radial basis functions and genetic algorithms. This technique was verified by fabricating and simulating bilayer cantilevers consisting of aluminum and glass (TEOS oxide) as well as polyimide and TEOS. The results obtained are very encouraging and call for more research in non-parametric based modeling for MEMS structures and their applications. A generalized Graphical User Interface (GUI) is designed in order to apply the proposed technique for other material properties and MEMS devices.

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Conference 6175: Testing, Reliability, and Application of Micro- and Nano-Material Systems IV

6175-01, Session 1

Metrology and materials characterization for nanoelectronics

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Recently, Hutcheson[1] found that the device dimensions have become small enough to proclaim that chips are now nano-chips. From this point of view, high volume manufacturing of nanotechnology is already a reality. However, those familiar with the semiconductor industry are asking another question: How long can scaling of today's nanoelectronics continue? The International Technology Roadmap for Semiconductors provides an answer to this question. The industry believes that extending CMOS technology through new materials and device structures will be possible for the next fifteen years. Recently, the semiconductor industry has started to refer to the new transistor designs that will enable this scaling as CMOS extension. There are two approaches to CMOS extension: planar and non-planar. One example of non-;planar CMOS is the FINFET. The gate length of any of these nano-transistors will shrink to less than 10 nm over this timeframe. Already, the electrical properties of nano-transistors have moved into a regime of short channel devices. Additional, new physics will manifest itself as scaling continues. The astoundingly small size and high density of nanoelectronics will challenge metrology and characterization and most certainly move measurement further into the world of nanotechnology.

In this paper, the limitations of metrology and characterization will be presented in terms of the new electrical properties of nano-devices. The long time goal of physical metrology has been and will be direct correlation of the physically measured quantities with electrical properties. The limitations and future needs of the measurement technology used to characterize and control Lithography, Front End Processes, and Interconnect and ultimately the electrical properties of the IC will each be discussed.

Metrology and characterization will certainly be impacted by the physics of nano-dimensions on the structures. For example, quantum confinement and strain will alter the optical properties of thin silicon layers in strained silicon on insulator and other engineered substrates. Measurement of thin films such as the gate dielectric on top of engineered substrates will require continuous improvement in optical modeling capability. Measurement of gate length will also be impacted by the new materials properties of thin lines and the engineered substrates below. When possible the nano-sized aspects of non-classical CMOS and future interconnect will be discussed along with the other challenges associated with new materials and scaled dimensions.

Scaling has made materials characterization increasingly important. For example, transistor cross-sections are routinely imaged using transmission electron microscopy. The electrical properties of interfaces between key device elements such as the interface between the silicon substrate and the gate dielectric play increasing more important roles. The near-monolayer nature of these interfaces requires atom-by-atom characterization. The last part of this talk will cover some of the key advances and future requirements of materials characterization methods such as the near atomic imaging ability of aberration corrected scanning electron microscopes.

6175-02, Session 2

High-resolution microscopy with x-ray and extreme ultraviolet radiation

G. P. Denbeaux, SUNY/Univ. at Albany

The availability of zone plate optics enables short wavelength imaging with a resolution below 20 nm. In the extreme ultraviolet (near 13 nm wavelength), this can be used for non-destructive imaging of defects buried within the multilayer masks used for Extreme Ultraviolet (EUV) lithography. In the soft x-ray range (near 2 nm wavelength), this can be used for direct measurement of the magnetization within individual layers of magnetic thin films. In both of these cases, the high resolution imaging is made possible by the diffractive optical elements that are fabricated with electron beam lithography.

EUV lithography is the most likely candidate for adoption by the semiconductor manufacturing industry as the next generation lithography technique. In this technology, reflective optics coated with Mo/Si multilayers that provide high reflectivity in a narrow band of wavelengths near 13-nm are used for imaging. One of the remaining issues to be solved before EUV lithography can be commercialized is the reduction of defects on multilayer-coated EUV masks. Zone plate microscopy using 13 nm radiation is an ideal technique to find and understand the defects since it non-destructively probes into the multilayer with high spatial resolution to find and characterize defects even when they are buried within the multilayer.

In order to understand the properties of magnetic thin films, it is often necessary to image the local magnetization. This imaging can be performed with x-ray microscopy using contrast obtained with x-ray magnetic circular dichroism, which allows direct imaging of the element-specific orientation of the magnetization within samples. For example, by changing the x-ray energy to the absorption edges of iron near 706 eV or cobalt near 777 eV, the magnetic orientation for each element can be imaged independently. Also, imaging with x-rays allows applied magnetic fields during exposures without affecting the resolution. Images of the magnetization of each layer within multilayered magnetic samples, and their response to applied magnetic fields will be shown.

The design and function of the x-ray and EUV microscopes and the diffractive optics will be presented. The results of the experiments with these microscopes will be shown along with other x-ray microscopy results including biological tomography and imaging of electromigration within Cu interconnects.

6175-03, Session 2

Critical shape metrology for nanoimprint lithography using x-ray scattering and reflectivity

C. L. Soles, R. L. Jones, H. Lee, H. W. Ro, A. Karim, E. K. Lin, W. Wu, National Institute of Standards and Technology

Nanoimprint lithography (NIL) is rapidly emerging as a viable next generation lithography capable of patterning features with dimensions of less than 10 nm. NIL is a form of printing whereby nanoscale features are written once into a master, typically Si, quartz, or some other hard material, using a high resolution but slow patterning technology such as electron beam lithography. This master can then be rapidly and repeatedly stamped into a softer resist film. This replication technique is a cost effective way to combine the high resolution of electron beam lithography with the throughput of a stamping process. However, the resolution of NIL exacerbates many of the shape metrology challenges currently facing optical lithography. Furthermore, the fact that NIL is a direct write, contact lithography introduces new metrology challenges previously not encountered with state of the art optical lithography. In this presentation we describe a suite of X-ray scattering and reflectivity measurements to address several of the critical challenges facing NIL. Two of these most pressing issues include (1) quantifying the fidelity with which the patterns in a master are transferred to the imprinted film and (2) quantifying the residual layer thickness. For the fidelity of pattern transfer issue, we have developed critical dimension small angle X-ray scattering (CD-SAXS) as a tool to quantify pattern shape with nm precision. CD-SAXS is a transmission scattering technique whereby an array of nanostructures serves as a diffraction grating. By rotating the sample and analyzing the resulting diffraction patterns, it is possible to quantify shape within arrays of nanostructures with periodicities ranging from 500 nm to 10 nm. This is done on both the mold and resulting imprint to define the fidelity of pattern transfer with unprecedented accuracy and without destroying the sample. For the residual layer, specular X-ray reflectivity (SXR) is introduced as a tool to extract this critical thickness in-situ, without cross-sectioning the pattern of interest. The residual layer is a thin layer of resist on the patterned substrate resulting from the fact that the imprint master cannot fully displace all of the resist and make direct contact with the substrate. By modeling the SXR data from either the mold or imprint with a multilayer recursive solution to a one-dimensional Schrödinger equation, we extract the electron density (proportional to the physical density) profile of the patterned film as a function of distance through film. This directly reveals not just the desired residual layer thickness, but also the pattern height and the average line-to-space ratio variations (in model parallel line space gratings) as a function of pattern height. If an absolute lateral length scale, such as pattern width, line width, or pitch is known, these line-to-space ratio variations can be combined with the pattern height to completely define the pattern shape. The power and utility of these non-destructive X-ray metrologies for quantifying the fidelity of pattern transfer and the residual layer thickness are illustrated for a range of NIL patterned samples.

6175-05, Session 3

Nanoscale deformation measurements for reliability assessment of material interfaces

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With the development and application of micro/nano electronic mechanical systems (MEMS, NEMS) for a variety of market segments new reliability issues will arise. The understanding of material interfaces is the key for a successful design for reliability of MEMS/NEMS and sensor systems. Furthermore in the field of BIOMEMS newly developed advanced materials and well known engineering materials are combined despite of fully developed reliability concepts for such devices and components. In addition the increasing interface-to volume ratio in

highly integrated systems and nanoparticle filled materials are challenges for experimental reliability evaluation. New strategies for reliability assessment on the submicron scale are essential to fulfill the needs of future devices. In this paper a nanoscale resolution experimental method for the measurement of thermo-mechanical deformation at material interfaces is introduced. The determination of displacement fields is based on scanning probe microscopy (SPM) data. In-situ SPM scans of the analyzed object (i.e. material interface) are carried out at different thermo-mechanical load states. The obtained images are compared by grayscale cross correlation algorithms. This allows the tracking of local image patterns of the analyzed surface structure. The measurement results are full-field displacement fields with nanometer resolution. With the obtained data the mixed mode type of loading at material interfaces can be analyzed with highest resolution for future needs in micro system and nanotechnology.

6175-06, Session 3

FIB-based measurement of local residual stresses on microsystems

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The rapid growing market for microsystems like MEMS, MOEMS, NEMS demands different measures to provide thermo-mechanical reliability of those systems over their exploitation time. Residual stresses are one of the crucial issues, because they are inherent to many of the micromachining processes. They superpose with functional or environmental loading during exploitation and can lead to early failure of the whole system. Consequently, their knowledge and control is a strong need designing new microsystems and their packaging. Most available today measurement methods for residual stresses suffer from the fact that they average over larger object areas and cannot be applied very locally, i.e. within areas of a micron or of even substantially smaller size. The developed by the authors approach intends to meet this goal, at the same time considering the method suitable for a variety of materials.

The presented stress measurement method bases on the specific testing feasibilities provided by focused ion beam (FIB) equipment. Ion milling is utilized to release very locally residual stresses on components of interest. Generated this way surface deformations around the milled area are measured by digital image correlation (DIC) algorithms. As a result originally existing residual stresses can be computed. Referring to the classical hole drilling technique, through holes have been milled in thin submicron membranes of Si3N4 as manufactured for MEMS devices. Residual stresses introduced by silicon micromachining have been determined from displacement fields around the holes. Comparisons between the analytical solution for the mechanical problem of stress release and the measured displacement fields show a good agreement. Algorithms have been developed, which aim at an efficient fitting of the analytical solution to measured displacement fields. In order to qualify this method for local residual stress measurements, results obtained by ion milling and subsequent DIC analysis have been proven by independent measurements of stresses from bulge testing of the same membranes under pressure.

Local measurement of residual stresses in thin film micro structures on substrates can be accomplished by ion milling of trenches into the thin surface layer. Finite element simulations have been used to allocate stress values to the measured displacement fields nearby the stress release trench.

In addition to a description of capabilities of the method, the authors present relevant applications to stress problems on MEMS and thin layer structures. Future improvements of the FIB based method are discussed with regard to size reduction of measurement areas and higher measurement sensitivity applying more sophisticated feature milling.

6175-08, Session 3

Micro/meso scale fatigue damage accumulation monitoring using nonlinear acoustic vibro-modulation measurements

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Monitoring the incipient damage at the earliest possible stage is essential for predicting structural performance and remaining fatigue life of structural components. Existing prognostic methodologies incorporate conventional SHM and NDE techniques responsive to cracks and delaminations resulted from the irreversible material fracture and disintegration at the macro-scale. There is an increasing need for technologies that could allow for monitoring material degradation at the micro/meso scale before the onset of the macro-scale fracture. In this contribution, we report results of the real-time monitoring of the material micro/meso scale degradation using the nonlinear acoustic vibro-modulation technique. The technique explores nonlinear acoustic interaction of the high frequency ultrasound and the low frequency structural vibration at the site of the incipient damage. The indicator of the damage severity, nonlinear acoustic damage index (DI), was measured in real time during the strain-controlled three-point bending fatigue test of aluminum and steel specimens. Nondestructively, degradation of the specimen was revealed through the increase in the DI, which correlated well with the respective decrease in the specimen's stiffness. Destructive SEM examination confirmed sensitivity of the DI to the incipient micro/meso scale damage and advocated for utilizing the vibro-modulation approach for assessment of material degradation before fracture.

6175-09, Session 3

Multiscale computational FEM-based engineering approach to modeling and evaluation of damping behavior of CNT-reinforced composite materials

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A novel concept of nanoparticle vibration damping [1, 2] shows the effect that molecule-level mechanism can have on the damping and that nanoparticles/fibres/tubes-reinforced materials can provide enhanced strength and vibration damping properties. It is particularly worth noting that carbon nanotubes can act as a simple nanoscale spring where rheological modelling can play a significant role while understanding of mechanics of novel systems across the scale length. The mechanisms involved in such materials need to be understood and the relevance to strength/damping identified. Additionally adequate modelling techniques for the next generation of vibration damping systems are technology gaps that need urgent consideration.

The computational models simulating mechanical properties range many scales starting from nano-scale (Molec. Dynam.), investigating the atomic interaction of the nano-particles in a very reinforcing material alone and its interaction with the atoms of matrix [3, 4], up to the description of such composite in large structures with dimension of several meters. The mechanisms involved in such materials need to be understood and the relevance to damping identified.

Our aim was to investigate and develop advanced computational FEM-based technique to estimate performance and mechanical/damping properties of nanoparticle/fiber-reinforced engineering materials and then, if successful, assemble them into viable engineering workbench. Carbon nanotube-reinforced structures are principally used at all phases of modeling and simulation. Thus we will form a bridge from the very basic research done by physicists and chemists to the practical applications by engineers.

To achieve the objective we performed the development of characterization and modeling technique of the fundamental phenomena that describe relationships between structure and mechanical properties of the materials, formalize the set of structural mechanical approaches to build a bridge between macro and nanoscales. Carbon-nanotube-reinforced composite material was simulated via advanced finite element and meshfree codes, using a hollow shell representation of the individual nanotubes. It's noted that the recently developed meshfree techniques for shells do not present undesirable membrane and shear locking phenomena, while these locking phenomena are inherent in the more commonly used finite element methods. Our computational approach is fundamentally equal simulation and modelling of materials with combined molecular dynamics (MD) and FEM technique, where an equivalency of each other is shown by mathematical analysis. This conclusion proves a joint application of MD and FEM principles in 2D/3D modeling of materials where stress-deformations are described in angle coordinates of sin and cos found through application of force field methodology and structural mechanic approach [3, 4].

A continuum model for deformation of material reinforced with nanoscale hard fibers/tubes has been developed. A model using the fast multi-pole method (FMM) is presented. The FMM uses the Taylor expansion of the integral equations describing the interaction of rigid inclusion with the closest neighbors and with the flexible matrix. The FMM models reduce drastically both computation time and storage requirements so that models, which were not possible to solve with present computational technique, are investigated. The method enables to solve the continuum containing up to millions of such inclusions in a computer by parallel algorithms.

In conclusion, it is worth noting that for a realistic simulation of the stability behavior of the nanoparticle-reinforced material, the nonlinear intramolecular inter-actions between neighboring atoms have to be taken into account. In order to reduce computational costs, it is necessary to develop advanced homogenization technique so as to apply shell elements in the model. Comparing to the FEM, the

new technique will introduce further reduction of both computer time and storage requirement. The results will potentially create fundamentals for investigation and development of 3-D reinforced composite structures with high nanoscale structures volume content, using nano-scale reinforcement architecture to reduce component mass and dimension.

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6175-10, Session 4

Ultrasonic atomic force microscopy and nanoindentation microscopy for characterization of functional nanomaterials

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Ultrasonic atomic force microscopy (UAFM) and nanoindentation (NI) incorporated in AFM have realized measurement of both topography and stiffness distribution for the first time, and they are now accepted as practical tools for evaluation of nanomechanical properties and subsurface defects in MEMS devices, ferroelectric materials and nano-composites. Here we present recent application of these methods to novel functional materials. We observed stress-induced ferroelectric domain switching, which would be important in establishing the reliability of piezoelectric actuators using ferroelectric materials. The stress was applied by NI within grains of soft PZT ceramic with a tetragonal structure (unpoled). In UAFM image at the 2nd deflection mode, stripe structures were observed showing periodic variation of the resonance frequency, which were caused by the stiffness anisotropy of the newly generated 90 degree domain structure. In evaluation of carbon nanotube (CNT) - polystyrene composite, NI, AFM and scanning electron microscopy were systematically applied to elucidate the significant difference between single-walled and multi-walled CNT.

6175-11, Session 4

Determination of deformation fields and visualization of buried structures by atomic force acoustic microscopy

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Advanced Scanning Probe Microscopy modes such as Atomic Force Acoustic Microscopy (AFAM) and Ultrasonic Force Microscopy (UFM) combine Atomic Force Microscopy (AFM) with ultrasound. These techniques become increasingly powerful tools for the determination of material properties on nanoscale.

Non-destructive evaluation of subsurface and buried structures is getting more and more important in semiconductor industries. Existing methods that allow subsurface measurements with nm local resolution are mostly based on destructive concepts as surface ablation by Focused Ion Beam. Supplementing Atomic Force Microscopy with ultrasonic excitation of the specimen enables non-destructive determination of subsurface and buried structures, with the inherent high local resolution of scanning probe techniques.

In AFAM, flexural and torsional cantilever vibrations are excited by out-of-plane and in-plane sample surface vibrations. The ultrasound is transmitted from the sample into the cantilever while forces act between sensor tip and sample. The sample surface is scanned by the sensor, and an ultrasonic image is acquired parallel to the topography image. The contrast comprehended in the ultrasonic image depends on surface topography and on the local elastic and adhesive properties of the sample. Voids, inclusions, or cracks, which build up regions of different elastic constants in the interior of the material, are sensed in the local elastic response by the tip. That way, information on hidden structures can be derived from images made visible by the acoustic excitation. This subsurface information is overlaid by additional topographic information, also contained in the ultrasonic image.

The solution described combines an Atomic Force Microscope and an ultrasonic excitation set-up with tensile and bending modules. It is innovative in generating deformation fields on surfaces of stressed objects and in in-situ imaging and analyzing of the deformation fields in the AFM. A software module for micro-deformation analysis by means of correlation based algorithms (MicroDAC) is used to determine the local surface deformation quantitatively. AFAM modes are used to examine local stiffness variations of the sample. Examples of stress fields in different materials are investigated and high-resolution images will be shown.

AFAM is mainly applied to the analysis of materials with elastic properties locally varying on micro- and nano-scale. Strain fields and buried structures can be visualized. The AFAM principle allows for the evaluation of porous materials, e.g. stacked layers, porous low-k, and hidden cracks in subsurface areas. With the introduction of new materials in semiconductor technologies, high-accuracy measurements of mechanical properties are increasingly important. AFAM constitutes an important technique for the development of new materials and for quality assurance in semiconductor production processes.

6175-12, Session 4

Nanoscale mechanical investigations of tin oxide nanobelts: absolute modulus measurements

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Semiconducting oxide nanobelts have been the focus of considerable experimental activity for applications in both nanoelectronics and nanosensors in addition to their importance in elucidating the properties of self-assembling inorganic nanostructures. Recently, nanomechanical analyses of individual SnO2 nanobelts have been reported4. Nanoindentation was utilized to investigate the inelastic mechanical response of nanobelts including hardness and the load profile for fracture propagation. Such information is critical for predictive reliability analyses of nanoelectronic or nanosensor devices incorporating such nanostructures. However, a nondestructive approach is preferred to enable eventual in situ mechanical analysis of nanobelt-containing device structures.

The elastic indentation modulus of SnO2 nanobelts has been investigated via nondestructive differential ultrasonic force microscopy (d-UFM) and atomic force acoustic microscopy (AFAM). The nanobelt crystal structure, as determined via transmission electron microscopy, was indexed to the tetragonal rutile structure (with lattice constants identical to those of bulk SnO2) as reported previously. The atomic Sn:O composition of the nanobelts studied was at or near 1:2. Topographic imaging studies revealed the nanobelt surface to be atomically flat with the exception of surface nano-dots, assumed to be local SnO2 crystallites. Local (10nm x 10nm) indentation modulus measurements were carried out via differential UFM on both the flat and nanodot regions of the nanobelt. Using the underlying Si substrate as a calibration standard the SnO2 modulus was estimated between 156 ±12 GPa and 144±12 GPa for two respective nanobelts, significantly lower than corresponding bulk values for any of the observed crystal orientations. A comparative evaluation was carried out using atomic force acoustic microscopy at the National Institutes of Standards and Technology (NIST) Laboratory at Boulder on the same nanobelt samples as investigated with d-UFM. Frequency tracking imaging of the nanobelts were comparative in contrast with UFM imaging. Likewise, AFAM point measurements on a selected nanobelt yielded an indentation modulus of 154 ±18 GPa, in good agreement with the d-UFM measurements. The agreement between these two techniques validates earlier d-UFM measurements on such nanobelts and confirms that the indentation modulus is significantly reduced in comparison with values calculated from bulk SnO2 elastic constants. These measurements imply that nanoscale mechanical properties of such materials can exhibit substantial deviations from corresponding bulk properties.

6175-13, Session 4

Near-field apertureless nanoRaman microscopy for measuring strain in silicon

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Recent advances in Si chip technology have exploited the electron mobility enhancements in strained crystalline silicon (strained Si) to boost the performance of Si field-effect transistors (FETs) for complementary metal-oxide semiconductor (CMOS) ICs. High spatial resolution, quantitative analysis and metrology of strain in FET device structures has traditionally exploited higher order Laue zone (HOLZ) line analysis using convergent beam electron diffraction (CBED). The introduction of silicon-on-insulator (SOI) technology to further enhance the performance improvements of strained Si has recently been explored by IC manufacturers. However, device fabrication on an SOI platform sharply limits the volume of crystalline Si in the vicinity of the FET channel. This has the potential to dramatically reduce the capability of CBED to accurately measure the Si strain due to HOLZ line broadening. Preliminary strain measurements on SOI-based devices suggest the presence of such an effect.2

Consequently, alternate analytical protocols require development for quantitative metrology of the local Si stress state in cross-sectionally prepared test structures of Si-based devices. One such technique is based on Raman microscopy. Raman microscopy probes stress in Si by directly measuring the resulting shift, in the Si optical phonon frequency. The spatial resolution of those techniques is typically in the regime of 400-1000 nm, although UV-based methods can achieve spatial resolution as low as 200nm. This resolution is insufficient for strain analysis in emerging device geometries down to the 45 nm node as noted in the ITRS roadmap.

A potential solution to this limitation exists in so-called apertureless near-field scanning spectroscopy. In this technique a Raman probe laser is used to illuminate a metallic nanoprobe tip positioned within a few nanometers of the surface of interest. The presence of a nanoprobe tip near the surface can dramatically enhance the emission of Raman-shifted photons. The present work has demonstrated the ability of such near-field apertureless nanoRaman to measure Si strain in a planar geometry. Strain-shift Raman spectra from a metallized nanoRaman probe tip has been acquired utilizing a horizontal tuning-fork approach in favor of shear-force tuning force or optical lever systems. Analyses have been carried out to isolate near-field photon scattering from bulk Si scattering. Large (50%) background Si peak enhancement has been observed and is attributed, in part, to tip-shadowing effects. A prelimary strain analysis based on p-polarization scattering is presented.

6175-14, Session 5

High spatially resolved nondestructive characterization of nanoparticles

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In forming and depositing nanoparticles by any method, several factors influence the properties achieved. This is true also for Laser ablation techniques. Properties concerned are especially the particle size and shape distribution. But also information about chemical, optical, elastic and crystalline properties are needed. So characterisation methods giving this information have to be developed and/or adapted as a support the development of nanoparticle synthesis.

We studied newly developed passivated nanoparticles by several high resolution microscopic methods as scanning electron microscopy (SEM), transmission electron microscopy (TEM) and scanning probe techniques especially atomic force microscopy in the non-contact mode. X-ray diffraction was used to give information about crystal structure and near surface chemical composition. The particles considered are Si, C, and Fe.

6175-15, Session 5

Synthesis and passivation of nanoparticles by pulsed laser ablation

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Nanoparticles are of interest because their unique properties may be considerably different than those of the corresponding bulk material. In the ideal case, one can synthesize isolated nanoparticles in order to take advantage of their properties. However, many synthesis processes produce a deposit in which the nanoparticles aggregate or coarsen (Ostwald ripening) to form larger particles. We have formed nanoparticles of Si, C, and Fe by pulsed laser ablation and have explored the feasibility of passivating these particles during the synthesis process in an attempt to minimize particle coarsening. Passivation was done by forming the nanoparticles in an Ar/N2 background, which allowed the formation of a thin nitride layer on the nanoparticle surface. In this paper we describe the synthesis procedure for synthesizing and passivating the nanoparticles.

6175-16, Session 5

The resistance to chloride penetration of concrete containing nanoparticles for pavement

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The resistance to chloride penetration of concrete containing nano-particles for pavement is experimentally studied in this work. Both nano-TiO2 and nano-SiO2 are respectively used to be as the additives. For comparison, the resistance to chloride penetration of plain concrete, the concrete containing polypropylene (PP) fibers and the concrete containing both nano-particles and PP fibers is also experimentally investigated. Nano-SiO2 in the amounts of 1% and 3% by weight of binder (the sum of cement and nano-particles) is used, and Nano-TiO2 in the amounts of 1%, 3% and 5% by weight of binder is employed. The content of PP fibers is 0.6 kg/m3 and 0.9 kg/m3.

The test results indicate that the addition of nano-particles improves the resistance to chloride penetration of concrete. The resistance to chloride penetration of concrete containing nano-TiO2 is better than that containing the same amount of nano-SiO2. The effectiveness of nano-TiO2 in enhancing the resistance to chloride penetration increases in the order: NTC5<NTC3<NTC1 (with the decrease on nano-TiO2 content). The resistance to chloride penetration of concrete containing 1% nano-TiO2 increases by 31%. Even for the concrete containing 5% nano-TiO2, the resistance to chloride penetration increases by 11.74%. The similar results can be observed for the concrete containing nano-SiO2, which indicates that the enhanced extent of the resistance to chloride penetration of concrete decreases with increasing content of nano-particles.

However, the resistance to chloride penetration of concrete containing PP fibers is reduced. The larger the content of PP fibers is, the lower the resistance to chloride penetration of concrete is. For the concrete containing both nano-particles and PP fibers, the resistance to chloride penetration is also decreased and even lower than the concrete only containing the same amount of PP fibers.

Finally, the relationship between the chloride diffusion coefficient and compressive strength of concrete is obtained from this test and approaches hyperbola basically, which indicates that the resistance to chloride penetration of concrete increases with increasing compressive strength and confirms that compressive strength is a critical factor affecting the resistance to chloride penetration of concrete.

6175-17, Session 5

The study on the size effect of microsize structures using the nanoUTM

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Generally, the deformation in the micro-scale is dependent on the size of specimen. Some theories such as the couple stress theory and strain gradient theory in the literature explain these phenomena. The purpose of this study is to investigate the size effect in micro-scale. Specimens that have various diameters such as 25, 30 and 50 μm are copper micro-wires. We carry out the tensile test to measure the mechanical properties and investigate the size effect using the nanoUTM.

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6176-01, Session 1

An examination of nondestructive evaluation techniques for polymer matrix composite sandwich materials

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Structural sandwich materials composed of triaxial braided polymer matrix composite material face sheets sandwiching a foam core are being utilized for applications including sporting equipment such as hockey blades. Hockey blades made from sandwich materials were examined with multiple nondestructive evaluation (NDE) techniques including thermographic, radiographic, and laser based methods to investigate the manufactured condition of blades and damage induced from play. Hockey blades in an as received condition and damaged blades used in play were investigated with each technique. NDE images from the blades were presented and discussed. Structural elements within each blade were observed with radiographic imaging. Damaged regions and some structural elements of the hockey blades were identified with thermographic imaging. Structural elements, damaged regions, and other material variations were detected with laser-based techniques in the hockey blades. Each technique's advantages and disadvantages were considered in making recommendations for future inspection of components made from these types of materials.

6176-02, Session 1

Self-diagnosis of damage in fibrous composites using electrical resistivity measurements

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Criticality of damage in aircraft and spacecraft structures cannot be easily determined due to the subsurface nature of particular failure modes. However, mechanical deformation and electric resistance of CFRPs are coupled, so that the material is inherently a sensor of its own damage state. Therefore, a practical technique for in situ damage detection and strain sensing in fiber-reinforced composite structures relying on "multifunctional" characteristics of the constituent materials can be possible. The objective of this research was to develop an integrated approach using extracted features from electrical resistivity measurements and coupled electromechanical models of damage, for in situ damage detection and sensing in CFRP composite structures. To achieve this objective, we introduced specific known damage (in terms of type, size, and location) into CFRP laminates and established quantitative relationships with the electrical resistivity measurements.

For processing of numerous measurement data, an autonomous data acquisition system was devised. We also established a specimen preparation procedure and a method for electrode setup. The fibers on the specimen surface were exposed using sand paper, and then silver paint was painted on the sanded regions to make connection points for electrodes. Copper electrodes were contacted with the silver paint, and pressure was imposed on the contacts by tightening bolts on the electrodes. Three different silver painting methods were considered: only the top surface of the specimen was painted, the top and bottom surfaces were painted, and the top and bottom surfaces were connected with silver paint by painting the trimmed edge. These three different methods were deployed and their results compared.

Coupon and panel CFRP laminate specimens with various specific known damage were tested and post-processed with the measurement data. Coupon specimens with various sizes of artificial delaminations obtained by inserting Teflon film were manufactured and the resistance was measured. The measurement results showed that increase of delamination size led to increase of resistance implying that it is possible to sense the existence and size of delamination. Encouraged by the results of coupon specimens, we implemented the measurement system on panel specimens. Three different quasi-isotropic panels were designed and manufactured: a panel with artificial delamination by inserting Teflon film at the midplane, a panel with artificial delamination by inserting Teflon film between the second and third plies from the surface, and an undamaged panel. The first two panels were designed to determine the feasibility of detecting delamination using the developed measurement system. The third panel had no damage at first, and then three different sizes of holes were drilled at a chosen location. The objective of the drilling was to evaluate the resistance changes and the possibility of sensing the location and size of holes. Panels were prepared using the established procedures with 6 electrode connections on each side making a total of 24 electrode connections for a panel. All possible pairs of electrodes were scanned and the resistance was measured for each pair. The results were post-processed using a GUI post-processing program to see the resistance changes in the axial, transverse, and diagonal directions graphically. The measurement results are promising for an in situ damage detection method for CFRP composite structures.

6176-03, Session 1

Damage localization in composite structures using wave based technique and matching pursuit decomposition

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Composite structures offer tremendous potential in aerospace, mechanical and civil engineering applications. An important element in achieving reliable systems is a strong capability of inspecting and assessing the physical condition of critical structural components. In terms of structural health monitoring, tasks focus on detection, localization and quantification of defects. This is accomplished through the interactions between structural features and multidisciplinary physical phenomena. In wave based approach, the presence of damage is visualized in terms of the changes in the signature of the resultant wave that propagates through the structure. In our present research surface mounted piezoelectric transducers have been used for monitoring purpose and the voltage output of each sensor is used for damage characterization. In this paper we propose a methodology to automatically analyze the time domain signal from delaminated structure and predict the location and size of the delamination. This has been accomplished by decomposing the signal in terms of its components using Matching Pursuit Decomposition technique and finally the time-of-flight information of these individual components are used to determine the location and size of the delamination. The assessment of delamination size and location is based on the mutual information shared by the neighbouring transducer sets. The final effort of this study would be to investigate several cases with different damage parameters and provide some information on the 'depth-wise' location of the damage.

6176-04, Session 1

Terahertz spectroscopy and imaging for the noncontact detection of foreign object debris in pre-cured composite layups

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The inclusion of foreign object debris (FOD) into composite layups is a real and recurring problem in the manufacturing of composite airframes. FOD can render a part as scrap or designate it for major rework, introducing large financial penalties to composite part fabrication processes. Traditional methods for identifying FOD (X-ray, ultrasound, eddy current, etc.) have several shortcomings including: precure inspection is not possible, contact is required with a part, only metallic objects can be detected, the part mold interferes with readings, or they require specialized and expensive backing material to be applied to prepreg fabric. In this paper, we demonstrate the efficacy of Terahertz (THz, or T-Ray) spectroscopy and imaging to detect a multitude of FOD types within aramid, glass, and carbon prepreg layups while on a mold. T-Rays are a type of electromagnetic radiation that exist between the Far-IR and microwave regimes and is promising for applications in the NDE arena. Non-contact measurement techniques based on THz can penetrate several layers of layup, and can identify different materials of FOD including plastic, metal, wood, and ceramic. In a spectroscopy setup, chemical signatures of various sub-surface materials can be collected allowing for their identification. In the imaging mode, images of buried FOD with lateral resolution better than 500 microns and depth resolution (determined by the Sparrow criterion) of better than 100 microns were attainable. There is large cost savings potential through the introduction of this technology into manual and automated layup process lines, by allowing rectification of problems before curing of parts.

6176-05, Session 1

Elecrical resistance change method for damage monitoring of woven graphite/epoxy laminates

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Laminated composite structures usually have a low delamination resistance. Since delamination cracks are usually invisible and difficult to detect by means of visual inspections, delamination cracks result in low reliabilities for the primary structure of laminated composites. In order to overcome these problems, many researchers have focused on smart composite structures that utilize the electrical conductivity of the reinforcement fiber, and damage-monitoring methods have been investigated. The authors, in our previous studies, proposed the identification of an internal delamination, the detections of matrix cracks and strain monitoring, using the electrical resistance change method, and confirmed the applicability of the method both analytically and experimentally. In the electrical resistance change method, damage to laminates such as delamination cracks are identified from the electrical resistance changes in the laminates. Since the method adopts reinforcement carbon fibers as sensors for delamination crack identification, the method does not result in the reduction in either the static or fatigue strength. For the measurement of the electrical resistance change, an electrical current is applied from electrodes that are mounted on the surface of a laminate. Therefore, the method is applicable to existing structures that have been fabricated without embedding sensors. In practical composite structures, a laminate whose surface layer is a woven ply, exists to prevent peeling of the surface layer. The electrical resistance change method positively utilizes the orthotropic electrical conductivity in the in-plane and in the thickness direction of graphite/epoxy laminates. The woven graphite/epoxy plies, however, have in-plane isotropic electrical conductivity in the plane of the ply, and a low thickness directional electrical conductivity is expected due to the undulating boundary of the graphite fiber bundles. The different electrical property of woven plies from the electrical property of unidirectional plies may cause different reactions when an electrical current is applied to the woven graphite/epoxy laminates. Moreover, it may be expected that the woven ply of the surface layer does not result in a good electrical contact. Since the electrical resistance change of the graphite/epoxy laminate due to damage such as delamination is very small, the reliability of the electrodes becomes a major issue for damage identification using the electrical resistance change method. The possibility of poor electrical contacts at the electrodes, therefore, requires us to investigate the reliability of electrodes for the laminate whose surface layer is a woven ply. In the present study, therefore, the applicability of the electrical resistance change method is investigated using beam type specimens, whose surface layer is a woven ply. First, the effect of the surface woven ply for the electrical resistance change method is investigated: the influence of an in-plane isotropic electrical conductivity of a surface woven layer upon the electrical resistance change is investigated both analytically and experimentally, and the condition of the electrical contact between the electrode and the specimen is investigated experimentally. Subsequently, the applicability of the electrical resistance change method for the beam type woven laminate specimen is confirmed experimentally by performing damage identification of the size and location of delamination cracks. A modified electric-bridge circuit for strain gages is employed to measure electrical resistance changes. The delamination crack is created by means of an interlamina shear test. For identifying damage location and size, the response surface, which provides the relationship between the electrical resistance changes and the damage size or location, is adopted. It is confirmed that the results of FEM analysis of the electrical potential distribution and the experimentally measured electrical resistance change are quite similar to the results of the unidirectional graphite/epoxy composites; the different electrical property of the surface woven ply from unidirectional ply is not critical for the application of the electrical resistance change method. As a result, the identification of the size and locations of delamination cracks using the electrical resistance change method can be done resulting in excellent performance. It is confirmed that the identification of delamination cracks with the electrical resistance change method is applicable.

6176-06, Session 1

Impact damage monitoring of CFRP using fiber Bragg grating ultrasound sensors

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Lightweight transportation has been strongly demanded for pollution reduction and increase in transportation capacity. From the viewpoint of weight saving, composites are good candidates for structural materials because of their superior mechanical properties compared with conventional metallic materials. Application of composite materials to aerospace structures has widely spread in these days. However, mechanical deterioration by impact damage remains a serious problem in composite materials. So, impact damage monitoring is very important to secure the reliability of composite structures. Recently, structural health monitoring using fiber-optic sensors has been paid much attention owing to their practical advantages such as easy installation, immunity of electromagnetic interference, etc.

In the present study, we attempted impact damage monitoring of composite by ultrasonic method using a fiber Bragg grating (FBG) which was one of fiber-optic sensors. 300 X 300 X 1mm3 cross-ply carbon fiber-reinforced plastic (CFRP) plate was used as test specimen for impact damage monitoring. A 9 X 13mm2 impact damage zone was introduced by ball dropping. Both FBG ultrasound sensor and piezoelectric ultrasound transmitter were attached on the CFRP surface. Broadband light is launched into the FBG sensor. Light reflected from the FBG sensor was transmitted through the optical filter whose transmissive wavelength range is comparable with the reflected wavelength range of the FBG sensor. Intensity of light transmitted through the filter is modulated by the vibration corresponding to ultrasound.

The change in response to ultrasound excited by either spike signal or toneburst signal before and after impact damage was investigated. In response to ultrasound excited by spike signal, the response after impact damage showed a broadened behavior where the period of response signal got longer. Ultrasound detoured around the damage area would have caused the broadened behavior in response signal. In response to ultrasound excited by toneburst signal, damage signal features broadened and distorted waveform in the latter response. Experimental results proved that the FBG inspection system could monitor a 9 X 13mm2 impact damage in CFRP.

6176-07, Session 1

Application of wavelet decomposition for damage monitoring of composite plates

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The application of composite materials has increased enormously due to high specific strength and specific stiffness afforded by these materials. Along with the tailored properties, the materials are also subjected to ever increasing demanding environments. Of interest is to monitor the health of structural components for structural integrity and safety assessment. This paper explores ideas from wavelet theory, fracture mechanics, and elastodynamics of laminated composite plates. We incorporate damage mechanics into composite plates and study the dynamics using algorithms developed using wavelet theory. The response from the elastodynamics behavior of the plate is analyzed by using adaptive algorithms based on wavelet theory. The major parameters of wavelets, namely, scale, position, and frequency are used in monitoring the responses of the structural component. The overall procedure is depicted in the figure shown below.

6176-08, Session 1

Cruciform specimen design for testing advanced aeropropulsion materials under cyclic in-plane biaxial loading

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Cruciform Specimen Design for Testing Advanced Aeropropulsion Materials under Cyclic In-Plane Biaxial Loading

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Abstract

Investigating material behavior under complex stress states is often done using in-plane biaxial loading approach. Utilizing such techniques requires using cruciform type specimens fornicated from plate material that are tested such as the specimen is gripped at four locations and loaded along two orthogonal axes. Servohydraulic systems are generally used in this application which is similar to those used for uniaxial testing. These kind of testing capabilities are currently being conducted at NASA Glenn Research Center via a new in-house testing facility. This is in support of the development of major and significant components of the Stirling Radioisotope Generator (SRG). It is also to assist in the progress of developing an analytical life prediction methodology [1] and to experimentally assist in verifying the flight-design component's life.

Further, this work is intended to carry the immediate goal of developing a speci-

men design that is fully compatible with the in-plane biaxial testing systems recently installed at NASA Glenn Research Center [2]. Thus, details of the specimen design and its applicability to the ongoing experimental activities are being reported and discussed. Finite element analyses were carried out to optimize the geometry of specimen and to evaluate the stress response under biaxial loading conditions [3, 4]. The material of interest used in this research work is nickel based superalloy. The data presented conclude that the specimen can be used to investigate the deformation behavior under general forms of biaxial loading, provided measurement and observation is limited to 1-in [2.54 cm] diameter circular region at the specimen center. However, the situation is more complicated in the case of experiments investigating strength and fracture behavior.

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6176-09, Session 2

Rotor fault diagnosis utilizing active magnetic bearings

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This paper conducts an analytical modeling effort and an experimental system design in order to assess the feasibility of utilizing active magnetic bearings (AMB) for rotor fault diagnosis. Mathematical models are developed in order to gain an understanding of the interaction between the rotor system and the AMBs (both conical and radial). The rotor system is in the form of a Jeffcott rotor, therefore, the set-up involves a rigid disk located mid-span on a flexible shaft with rigid supports (i.e., traditional ball bearings providing support). Based on the modeling results, the AMBs are located along the shaft between the ball bearings and the disk, and are designed to act as actuators (force inputs) and sensors (force and displacement responses) with the sole purpose of damage assessment through selected modal excitations of the rotor. The excitations as well as the recorded responses are both axial and radial. Again, at this point the AMBs are not expected to act as structural supports, although, future work will aim to use the AMBs as both structural supports and damage assessing actuators/sensors. The physics based models are used to define the domain for the required force inputs (i.e., the magnetic actuation signals) that excite particular system modes aimed at revealing various types of rotor damage. An important goal of this structural health monitoring procedure is the identification of disk cracks and shaft cracks due to their catastrophic and costly failure modes, especially in the aerospace field. Lastly, considering the modeling results and program requirements an experimental system design is presented.

6176-10, Session 2

A comparison of time series analysis algorithms for detection of barely visible impact damage in UAV wings

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We investigate the use of a vibrational approach for the detection of barely visible impact damage in a composite UAV wing. The wing is excited by a shaker according to a predetermined signal, and the response is observed by a system of fiber Bragg grating strain sensors. We use three different driving sequences: a stochastic signal, the output from a chaotic Lorenz oscillator, and gust loading to model the vibration experienced by a UAV in flight. On these data we apply a variety of time series analysis techniques to detect, quantify, and localize the damage incurred from a pendulum impactor, including classical linear analysis (e.g. modal analyses), as well as recently developed nonlinear analysis methods. We compare the performance of these methods, investigate the reproducibility of the results, and discuss issues with adaptation of the algorithms to a real-time continuous system health monitoring setting.

6176-11, Session 2

Spatial wavelet analysis for damage identification in a plate-type structure

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Performance of a dynamics-based damage identification technique depends on the quality of the measured data. In many cases, the experimental data, especially at low modes, are affected by interference such as ambiance noise and testing conditions, which can lead to misidentification or inaccuracy of the results. Applying a proper post-processing procedure for the measured data will increase the effectiveness of the identification performance. The successes of the dynamics-based detection procedures also require information of the original state of the structure to locate the damage, which is in many cases are not available. Elimination of original data dependency in damage detection will increase the versatility of the identification technique.

A new method for the enhancement of dynamics-based damage identification is introduced. Wavelet analysis of spatially distributed dynamic response measurements is employed to identify damage in a plate structures. Local perturbations due to damages that may not be visible in the response data are often quite discernable in the wavelet analysis. The wavelet transform is applied directly to the spatially distributed dynamic response signals, by modifying the time (t) in the wavelet transform function with the spatial coordinate of the corresponding signal data. In this study, we use the signals from the operational deflection shapes (ODSs). The technique is demonstrated on plate samples with various types and degrees of damages, including localized type of damage (i.e., crack) and area damage (i.e., impact or delamination). The operational deflection shapes of the plates are obtained by scanning laser vibrometer (SLV). Then, these modes are analyzed with the wavelet transform, where a sudden change in the spatial variation indicates the location of damage in the plate. Due to the multiresolution properties of the wavelet transform, this technique is expected to have high sensitivity to small damages or barely visible damages. Additionally, the application of wavelet transform procedure eliminates the requirement for the original state data of the structures. Sensitivity analysis of both the experimental procedure and identification technique are further performed to address the viability of the procedure. The proposed technique using the spatial wavelet analysis and operational deflection shapes from SLV promotes the effectiveness of damage identification of plate-type structures.

6176-12, Session 2

Correlation and validation of finite element models to large scaled composite UAV wings, healthy and damaged, for vibration-based damage detection

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Carbon-fiber-reinforced-polymer (CFRP) composites represent the future for advanced lightweight aerospace structures. However, reliable and cheap techniques for structural health monitoring (SHM) and damage detection must be developed and implemented before full confidence can be gained in the technology. Modal and vibration-based analysis can give potent information on a structures internal state, and combined with validated finite element models will provide powerful capability for SHM. Finite element (FE) models, however, can easily give spurious and misleading results leading if not finely tuned and validated. These problems are amplified as application of methods moves from simple academic structures to more realistic complex structures. In studying damage detection development on realistic structures it is therefore important to ensure the finite element model is well correlated and to gain a detailed understanding into the validity of the model, and hence damage detection capability.

Work towards addressing the question of model validity and its impact on damage detection for a realistic aerospace structure is presented herein. A small series of all-composite test pieces emulating wings from a lightweight all-composite Unmanned Aerial Vehicle (UAV) were developed to support damage detection and SHM research. Each wing comprises two CFRP prepreg and Nomex honeycomb co-cured skins and two CFRP prepreg spars-main and aft-bonded together in a secondary process using a well qualified structural adhesive to form the complete final wings. The first of the set is fully healthy-undamaged-while the rest have damage in the form of disbonds built into the main spar bondline. A detailed FE model was created of each of the four structural components and the assembled structure. Each wing component piece was subjected to modal characterization via combinations of a scanning laser Doppler vibrometer (SLDV) and hammer-accelerometer testing before assembly. These results were then used to correlate and validate the FE model on a component-basis, as the first step of a two-step full correlation process. Assembling and testing the full wing-the second step-

allows insight into modeling and correlating the adhesive bondlines, and hence the entire structure. After the capability to correlate and validate a complete healthy wing was developed, the process was extended to the damaged wings, and the ability of the FE models to accurately simulate the response of the entire wing with damage was studied. Based on the success of the models in simulating healthy and damaged cases of the complex aerospace structure, a broad range of existing damage detection methods are evaluated for their ability to locate the damaged region in the wing.

6176-13, Session 2

Structural damage identification of plate structures based on frequency-response function and natural frequencies using smart sensors

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Abstract

In this paper, a structural damage identification method (SDIM) is developed for plate like structures. It is derived using dynamic equation of undamaged/damaged plate, in which local change in flexural rigidity are characterized using damage distribution function. This SDIM requires to modal data in the intact state and frequency response of damage state where most of vibration based damage identification techniques requires to modal data in both states. Change of mode shapes of damaged plate are approximated as a linear combination of mode shapes of intact plate and are considered in dynamic equation of damaged plate. Constant Coefficients of linear combination have been evaluated using perturbed equation of motion and damage distribution function. Two strategies for making the inverse problem damage identification are introduced in connection with damage the present SDIM: (1) by using sensitivity of natural frequencies and (2) by using FRF-data, a sufficient number of equations can be derived to detect magnitude and location of damage. The feasibility of presented method is validated through some numerically simulated and experimental damage identification test using piezoelectric sensors and taking into account random noise in FRF-data.

Introduction

Occurred damage within a structures leads to change of structural vibration characterizes and can be used in turn to detect, locate and quantify existence structural damage. The finite element model (FEM) update techniques have been proposed in the literature. As a drawback of FEM-update techniques, the requirement of reducing FEM degrees of freedom or extending the measured modal parameters may result in the loss of physical interpretability and the errors due to the stiffness diffusion that smears the damage-induced localized changes in stiffness matrix into the entire stiffness matrix.

The modal-data-based SDIM have some shortcomings. First, the modal data can be contaminated by measurement errors as well as modal extraction errors because they are indirectly measured test data. Second, the completeness of modal data cannot be met in most practical cases because they often require a large number of sensors. On the other hand, using measured FRFs may have certain advantages over using modal data. First, the FRFs are less noise contaminated because they are directly measured from structures. Second, the FRFs can provide much more information on damage in a desired frequency range than modal data are extracted from a very limited number of FRF data around resonanc. Thus, the use of FRFs seems to be very promising for structural damage identification.

How to minimize the experimental measurement errors, structure model errors, and the damage identification analysis errors has been an important issue in most structural damage identification researches. Some researchers have investigated the damage-induced changes in natural frequencies, mode shapes, and curvature mode shapes with varying the location and severity of a damage. However, very few attentions have been given to the effects of the change of mode shapes, damage-induced coupling of vibration modes and the higher vibration modes omitted in the analysis on the accuracy of predicted vibration characteristics of the damaged beam, from a damage identification viewpoint.

The purposes of the present paper are: to develop an FRF-based SDIM, to investigate the effects of the mode shape changes and the omitted higher vibration modes on the accuracy of predicted vibration characteristics of the damaged beam, and finally to verify the feasibility of the present SDIM through some numerically simulated damage identification tests.

6176-14, Session 3

Health monitoring of aeronautical structures based on vibrations measurements

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Purpose of the paper is to present an innovative application inside the Non Destructive Testing field based on vibrations measurements, developed, at the Department of Aeronautical Engineering of the University of Naples “Federico II” (Italy), by the authors during the last three years, and already tested for analysing damage of many structural elements. The aim has been the development of a Non Destructive Test (NDT) which meet to most of the mandatory requirements for effective health monitoring systems, simultaneously reducing as much as possible the complexity of the data analysis algorithm and of the experimental acquisition instrumentation; these peculiarities may, in fact, not be neglected for an operative implementation of such a system. The proposed new method is based on the acquisition and comparison of Frequency Response Functions (FRFs) of the monitored structure before and after an occurred damage. Structural damage modify the dynamical behaviour of the structure such as mass, stiffened and damping, and consequently the FRFs of the damaged structure in comparison with the FRFs of the sound structure, making possible to identify, to localize and quantify a structural damage. The activities, presented in the paper, mostly focused on a new FRFs processing technique based on the determining of a representative “Damage Index” for identifying and analysing damage both on real scale aeronautical structural components, like large-scale fuselage reinforced panels, and on aeronautical composite panels. Besides it has been carried out a dedicated neural network algorithm aiming at obtaining a “recognition-based learning”; this kind of learning methodology permits to train the neural network in order to let it recognises only “positive” examples discarding as a consequence the “negative” ones. Within the structural NDT a “positive” example means “healthy” state of the analysed structural component and, obviously, a “negative” one means a “damaged” or perturbed state. With this object in view the neural network has been trained making use of the same FRFs of the healthy structure used for the determining of the Damage Index, as positive examples.

From an architectural point of view magnetostrictive devices have been tested as actuators, and piezoceramic patches as actuators and sensors. Besides it has been used a laser-scanning vibrometer system to validate the behaviour of the piezoceramic patches and define their technical parameters in order to lay the bases for design a light and reliability system. These techniques promise to bring a step forward for the implementation of an automatic “health monitoring” system which will be able to identify a structural damage in real time, improving the safety and reducing maintenance costs.

6176-15, Session 3

Nondestructive evaluation of metal-to-metal adhesive joints using vibration analysis: experimental results

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Note: This is an extended abstract to be considered for the best student paper award.

The use of adhesives in metal-to-metal structural joints has found limited applications due to a lack of reliable non-destructive evaluation (NDE) methods. NDE of adhesive joints is complicated by the composite nature of their construction and large differences in material properties. The need for robust NDE techniques that can effectively assess both adhesive and cohesive properties of an adhesive joint drives research in this field.

Vibration analysis (VA) is a well known NDE approach that shows promise for damage detection in adhesive joints. VA uses the dynamic response of a structure to estimate modal parameters that can be correlated to its state of health. Research involving VA of adhesive joints has focused primarily on manufacturing defects, not defects associated with stress-induced creep, and has to date yielded mixed results. Stress-induced defects (SID) tend to arise in regions of peak stress, whereas manufacturing defects may occur anywhere in the adhesive layer. Therefore the impact of SID on modal parameters may differ from the influence of manufacturing defects. This research investigates the correlation between SID and modal damping (MD) estimates in metal-to-metal adhesive joints.

In order to use MD as a damage indicating parameter it must be estimated precisely. There exist several methods to estimate MD, but the accuracy of these estimates can vary with the method of measurement. Because the mechanics of damping in structural adhesive joints are inherently nonlinear, the significance of specific mechanisms depends on the amplitude and frequency of applied loads. For this reason, identified MD values are frequently dependent on the amplitude of excitation, necessitating the need for constant force structural excitation. It has been shown that the free-decay envelope method provides accurate estimates of MD in structural adhesive joints, hence this method was chosen for the experimental phase of this work.

Experiments were conducted to investigate the dependence of modal damping ratio (MDR) on damage levels in metal-to-metal adhesive joints. Single lap aluminum specimens were bonded with epoxy and subjected to a sequence of tensile

loadings and dynamic response measurements. Tensile loads were applied incrementally in stages to induce various levels of damage in the adhesive. Viscoelastic creep in the adhesive was induced by limiting the loading rate. The dynamic response of each specimen to impact excitation was measured before and after each stage of loading, corresponding to response measurements at different levels of damage. The impacts were delivered using a customized impact hammer to ensure consistent peak amplitudes and eliminate amplitude-dependent nonlinearities in the response profiles. This hammer allowed precise and repeatable control of impact location, angle, and duration and enabled accurate estimation of MDR.

Three fundamental resonant frequencies were identified and corresponding MDR were estimated. The results revealed that MDR correlates well with damage magnitudes, increasing significantly with the progression of damage, indicating that VA may be an effective tool for NDE in structural adhesive joints. The estimated resonant frequencies, however, showed only marginal correlations to damage. Hence resonant frequency does not appear to be an effective parameter for damage detection in these specimens. It was also noted that the MDR of the second vibration mode exhibited more variation with damage than the other modes.

A finite element analysis (FEA) of the lap joints was undertaken in order to confirm the experimental results. A 3D finite element model of the lap joints was developed using ANSYS(r) and modal analyses were performed. Comparing resonant frequencies derived from FEA to experimental measurements verified the accuracy of the FEA model. It is known that if defects are in regions where the stress inflicted by a particular mode is maximum then the modal parameters of that mode show greater variations, and FEA revealed that peak stresses in the adhesive layer were associated with the second bending mode. This explained why experimental mode two MDR showed the greatest correlation with progressive damage.

6176-16, Session 3

On roughness-based damage detection method

J. Wang, North Dakota State Univ.

Details of a new damage detection technique using roughness profile of structural mode shape are presented in this paper. To simulate a damaged beam numerically, a simplified solution of free vibration of a multi-cracked beam is obtained using general function. Numerical filter is used to extract roughness profile from the mode shape of the beam. The location of a crack in a beam is then determined by a sharp peak value appearing on the roughness profile. The size of the crack is also determined by the peak roughness value at the location of the crack. Specifically, two types of numerical filters, i.e., triangular and Gaussian, are examined. It has been found the former filter is more effective in damage detection than the latter one. Calculations show that a relatively low measurement resolution is required by the roughness-based method. Noise stress tests are also carried out to demonstrate the effectiveness and robustness of this method under the influence of noise. As verification, the proposed method is applied on the experimentally measured curvature mode shape to detect damage in a carbon/epoxy composite beam. The successful detection of crack in the composite beam demonstrates that the roughness-based method can be used efficiently and effectively in damage identification and health monitoring of beam-type structures.

6176-17, Session 3

Fault detection and localization using measured surface vibration and local inversion

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We present progress we have made in developing a structural acoustic - based methodology allowing interior fault detection and localization in plate-like structures using only processed vibration data readily available on the structure's surface. The focus of our structural acoustic research and development efforts thus far can be summarized by the following question: Given sufficient but readily accessible displacement information over the surface of a vibrating structure, can we develop and implement corresponding local inversion algorithms for mapping material parameter variations, detecting and localizing flaws (cracks, voids, delaminations, etc.), and uncovering the depth profiles of such? Our methods use measurements of surface displacement associated with vibration of the structure caused by externally applied forces. These forces can be created simply by a local actuator in direct contact with the structure or in some cases by an incident airborne acoustic wave. We choose to rely on surface displacements because these are readily accessible for all materials and most structures using existing scanned sensor technologies such as laser Doppler vibrometry or high density arrays of surface mounted accelerometers.

The measured normal surface displacements, u(x,y), are then inverted locally using various mathematically optimized algorithms in order to obtain a desired material parameter - for example, the elastic modulus - whose spatial variation then serves to detect and localize the fault. This processing includes both so-called "weak" and "strong" direct local inversion algorithms based on the equations of motion, generalized force mapping based on some knowledge of the material parameters and the inhomogeneous equations of motion, w-k mapping with spatial windowing, and in limited cases direct observation of the measured surface displacement distribution.

This structural acoustic approach is not limited to any particular length scale requiring only that the structure be mechanically excited at frequencies for which the structural wavelength is within an order of magnitude of the fault dimension and that the dynamic surface displacements be mapped with a spatial resolution smaller than the fault size. We have demonstrated this approach on problems whose fault sizes range from tens of centimeters down to tens of microns. For example: we have successfully deployed the structural acoustic technique in the US Capitol Building to locate threatening deconsolidation and delamination effects within plaster walls and ceilings bearing large expanses of precious nineteenth century frescoes; we have been able to detect and locate de-bonding of thin (~ 1mm) stiffeners and frames in composite airframe skins in laboratory experiments; and we have been able to detect and locate faults in silicon micro-oscillators and their supporting structures with resolutions approaching 1 micron.

In this article, we will present the details of the structural acoustic approach to fault monitoring, describe various "inversion" algorithms for extracting the fault information, show the results of numerical feasibility studies, discuss the associated measurement technologies, and then present applied studies we have carried out using this methodology.

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6176-18, Session 3

Finite element design study of a bladed rotating disk subject to cracking under typical turbine engine loading conditions: part II

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Finite Element Design Study of a Bladed Rotating Disk Subject to Cracking under Typical Turbine Engine Loading Conditions, Part II.

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Abstract

Health management development for advanced propulsion systems and ultrasafe engine technologies continue to be among the NASA's aviation safety program's goal. It is to assist in predicting, detecting, preventing, and overseeing safety-significant propulsion malfunctions. The primary goal is to minimize the number of propulsion system faults that leads or contribute to civil aircraft accidents. Moreover, the health monitoring of essential and key components in aircraft engines such as rotors is increasingly gaining interest among engine makers and aviation safety government institutions. This is due to the fact that it is becoming rather necessary to impose safety conditions during operation and to the need for lower maintenance costs. In return, this assures that having reliable diagnostic tools for damage detection and health monitoring of rotating components is important in maintaining engine safety and reliability.

This paper represents a supportive analytical study undertaken finite element analyses as a means to study the durability issues of a propulsion component such as a rotor disk. The analyses are carried out under representative engine loading conditions to further investigate the application, the performance and the functionality of a crack detection system. Rotational speeds in the range of 2000 to 10000 rpm are used. Several key design parameters such as center of mass shift, induced cracks that ranged in length from a minimum of 0.2 to a maximum of 2.0 inches, attachment blades and typical holes within the disk are all being explored to study their influence on the crack detection system performance. Additional activities include presenting experimental data to compare analytically derived results with those obtained from the experiment to verify the effectiveness and the applicability of the system. Results showing relevant influence of these parameters on the performance of the disk and the crack detection systems are presented.

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6176-52, Poster Session

A pre-stack reverse-time migration method for multidamage detection in composite structure

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Lamb waves have been extensively considered in nondestructive evaluation and structural health monitoring because of their guided nature and ability to propagate in large areas. However, their dispersive nature and complex mode conversion phenomena often limit their uses in damage detection, especially in multi-damage detection.

In this paper a pre-stack reverse-time migration concept of transient waves signal processing techniques is developed and adapted to guided-wave propagation in composite structure for multi-damage detection by experimental studies.

An anisotropic laminated composite plate with a surface-mounted linear piezoelectric ceramic (PZT) disk array is studied as an example. At first, first-order shear deformation laminate theory is used to model Lamb waves propagating in laminates with a two-dimensional explicit finite difference algorithm. The phase and group velocities of flexural waves are also derived from dispersion relations.

Then the fundamental narrowband ultrasonic Lamb wave fields in the plate are alternately actuated and received using the linear array distributed piezoelectric transducers before and after damages occurred. The signals received from sensors by excitation of incident wave from the actuator consist of waves scattered from the damages and reflected from plate edges. The wave field solely reflected from the damages can be obtained by subtracting the wave field without damage from that with damages. Thus the synthesized reflected wave field with damages could be obtained.

A pre-stack reserve time migration technique, which is widely used in geophysical prospecting, is then performed to back-propagate the reflected energy to the damages using the same finite difference algorithm and locate multiple damages. It consists of three parts. The first is computation of the excitation-time imaging condition in the image space. Using ray tracing, the imaging condition for each actuator exciting the waves can be constructed by forming the incident wave front locus at each reserve time step. Then the locus data are saved as a reference table in a computer. The second step includes backward extrapolation of the reflected wave field in time. It can be executed by a full-way finite difference scheme and application of the pre-computed imaging conditions performed at each finite difference step. When the reverse time reaches zero, the imaging process is completed. By exciting the waves from another actuator location, and repeating the two procedures above, another image can be formed. The third procedure is to stack these imaging results in terms of the velocity of the transverse deformation to visually display the damages.

The validity of this method has been demonstrated through several groups of experiments. The first group shows the dispersion relations changing with different frequencies at different directions. In addition, the second one validates the group velocities of selected wave mode computed by laminate theory in different directions at a fixed frequency. The third group carries out the pre-stack reserve time migration technique, in which multiple damages can be successfully identified and the resulting image correlates well with the target damages.

According to the applicability of this pre-stack reserve time migration method, it is promising scheme for in-service monitoring of aerospace, civil and mechanical systems.

6176-53, Poster Session

Fiber optic strain monitor for an uninhabited aerial vehicle

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The Institute for Scientific Research, Inc. (ISR), in collaboration with the Naval Research Laboratory (NRL), will build and operate portable real-time fiber Bragg grating interrogator systems for monitoring strain in a small uninhabited aerial vehicle (UAV) of composite construction. Because of the small size of the ISR UAV, weight and volume are restricted, necessitating considerable redesign of laboratory interrogators to meet UAV constraints. NRL will supply a multiplexed interrogator for monitoring structural response rates up to about 10 kHz, while ISR will develop an optical frequency domain reflectometry (OFDR) system for measuring lower frequency response below about 100 Hz. The OFDR system will test a special differencing technique to separate strain induced signals from environmentally induced signals. A National Instruments CompactRIO system with a 3 million gate field programmable gate array (FPGA) and a 200 MHz Pentium processor will be used for real-time data acquisition and onboard signal analysis. The CompactRIO system weighs about 1.6 kg, measures 18cm x 9cm x9cm, consumes less than 5 W of power, and withstands over 50g of shock. Lithium polymer batteries will be used to power the system for flight times up to about one hour in the present configuration. While the near-term objective of this project is to overcome the challenges of applying fiber-optic strain monitors to aerial vehicles, the longer-term objective is to develop a system for detecting damage in aerial vehicles by analyzing structural response to chaotic vibration. Chaotic vibration of the airframe will be produced from random aerodynamic vortices. There is evidence that attractor based methods applied to airframe response to these ambient chaotic vibrations will provide a very sensitive indication of damage.

6176-54, Poster Session

Development of a resonant passive repeater for the enhancement of sensitivity and specificity in a wireless eddy current sensing scheme

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It is not an easy task to get information on the condition of the steel beam or rebar located deep in the cementitious materials simply by scanning the surface with the testing equipment because the distance between the equipment and object under test can be an obstacle to the acquisition of a correct data without any direct connection from the testing instrument to the object under test. To find an accurate but easily implementable and nondestructive evaluation method for the conductive medium deeply imbedded in the reinforced concrete of the civil infrastructures, the eddy current NDT technique may be used because it uses the conducting properties of object under test for the operation that good conductivity of steel or rebar can be properly exploited. However, it is not easy to apply the present eddy current NDT method to health monitoring for civil infrastructures because there is not strong enough magnetic coupling between test probe and DUT due to the considerable gap between the probe and the metallic materials used in civil structures. Thus, the read range of present eddy current NDT technique is not long enough to ensure the direct application of present techniques to the health monitoring of civil infrastructures. Another limitation that should be taken into consideration is that present eddy current applications are developed under assumption the surface of inspected material must be accessible to the probe. Therefore, the rough surface finish, as is often the case with civil infrastructures, may degrade the sensitivity of a detection test.

In this paper, to address the limitation inherent to the present eddy current NDT application and improve the sensitivity, our proposed scheme is to place an additional passive resonant repeater between conductive medium and probe.

In addition to the enhanced sensitivity which was experimentally ascertained, a resonant passive repeater can minimize the effect of surroundings on the target spots or materials because it uses locally limited current distribution. The proposed design is a sort of wireless sensor system because it does not need any electrical connection to the sensor and sample material under the sensor. No explicit connection from sensor to the driver makes it easier to use and implement and leads to a low loading effect. The sensor system can be modeled accurately in an equivalent circuit and have wide range of operating frequency. Furthermore, the cost of building a passive repeater can be very low, and an easy and fully developed fabrication processes can be used. Thus, manufacturability of the proposed sensor system can be quite excellent.

As mentioned previously, the proposed scheme using an inserted resonant passive repeater has not only many benefits of present eddy current NDT technique but also improved sensitivity and read range.

6176-55, Poster Session

Flexible ultrasonic guided wave sensor development for structural health monitoring

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Conference 6176: Nondestructive Evaluation and Health Monitoring of Aerospace Materials, Composites, and Civil Infrastructure V

Ultrasonic guided wave based technologies are commonly used in nondestructive evaluation (NDE). With the merits of long distance monitoring potential, easy accessibility for in service structural components, and wireless interrogation potential, ultrasonic guided waves have attracted much research attention in structural health monitoring (SHM). Guided wave transducers made of piezoelectric polymer PVDF are conformable to the curvature of a structural surface. They also have the great potential to be permanently embedded in aerospace, civil, and mechanical infrastructures. PVDF based transducers are also very cost effective, which makes them a good candidate for applications requiring a large number of sensors in room temperature monitoring environments.

This paper integrates the wave propagation and damage interrogation mechanics into SHM transducer design. A hypothesis for quick guided wave mode selection based on wave structure and power flow distribution are brought forward in our study. According to this hypothesis, guided wave modes particularly sensitive to surface corrosion and appropriate for damage assessment are selected. PVDF sensors are designed to generate the selected wave modes. Electrode patterns are fabricated on cost effective flexible polyimide based printed circuit boards. The excitability function of the selected wave modes are modeled with the finite element method. Considerations of wave excitation, propagation, and receiving are integrated to achieve optimized signal to noise ratio of PVDF transducers in damage detection.

Corrosion and erosion have become major concerns for aircraft and helicopters. A sample problem is presented in this paper on erosion monitoring of a 1mm thick aluminum plate. A simulated erosion process is introduced into the test structure in an area of 7mm diameter with 0.1mm step by step progression. Eight PVDF sectioned annular array transducers are used to monitor the erosion process. Damages are clearly detected with ultrasonic guided wave pulse echo and through transmission tests. The relation between echo signal amplitude and erosion depth are found to be related to the guided wave modes used in monitoring. A proper mode selection leads to a quasi-linear relation between the defect influence and defect size. However, for some other wave modes, the relation is highly non-linear.

Computed Tomography (CT) and a Reconstruction Algorithm for Probabilistic Inspection of Damage (RAPID) are used to localize the damage site and to assess the severity of the erosion damage. Back projection and algebraic reconstruction CT algorithms developed in medical ultrasound imaging and seismology are introduced into the area of ultrasonic guided wave tomography. Based on these algorithms, multi resolution algebraic reconstruction (MART) technology is developed in our research to achieve better defect localization resolution. The RAPID algorithms is a line of site reconstruction algorithm with probabilistic diffraction compensation. Both CT and RAPID algorithm give good defect localization and progression signatures of the test structure.

6176-56, Poster Session

Applying the Dempster-Shafer theory to fuse NDI data of fuselage lap joints

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The success of applying Dempster-Shafer theory for data fusion depends on how the basic probability assignment (BPA) or probability mass function is decided. In the case of nondestructive inspection (NDI) of aircraft lap joints, the inspection data is presented in raster-scanned images. These images are discriminated and modeled by iteratively trained classifiers. The classification error is used to represent the uncertainty for each trained classifier respectively. The BPA is defined based on the conditional probability of information classes and data classes, which are obtained from ground truth data and NDI measurements respectively. The Dempster rule of combination is applied to fuse multiple NDI inputs. The maximum mass outputs determine the final classification results, which present the estimation of remaining thickness due to corrosion. In this work, conventional eddy current and pulsed eddy current techniques were employed to inspect the fuselage lap joints of a service-retired Boeing 727 aircraft. The ground truth data, which was used as references for classifier training, was obtained by a teardown inspection with the digital X-ray mapping technique. The experimental results verify the efficiency of the proposed method.

6176-57, Poster Session

Combined experimental and analytical study using cruciform specimen for testing advanced aeropropulsion materials

A. Abdul-Aziz, NASA Glenn Research Ctr.

Combined Experimental and Analytical Study Using Cruciform Specimen for Testing Advanced Aeropropulsion Materials

Under In-Plane Biaxial Loading

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Abstract

A new in-house test capability has been developed at the NASA Glenn Research Center to conduct highly critical tests in support of major and significant components of the Stirling Radioisotope Generator (SRG). It is to aid the development of analytical life prediction methodology [1] and to experimentally assist in verifying the flight-design component's life.

Components within the SRG such as the heater head pressure vessel are to endure very high temperature environment for a long period of time. Such conditions are expected to impose life-limiting failure means of material creep and a slow gradual increase in strain witch will lead to an eventual failure of the pressure vessel. Furthermore, to properly evaluate the performance and assist in the design of this component, conducting typical traditional uniaxial tests may not provide the data needed due to the fact that the heater head is subjected to biaxial state of stress. Therefore, investigating the material behavior will have to be performed under in-plane biaxial loading conditions. Thus, the current work will undertake conducting experiments under equi-biaxial and non-equi-biaxial loadings situations at combined various temperature emulating creep environment. Cruciform shape specimen is to be utilized to conduct these series of tests [2]. Complementing these experimental activities is followed by performing detailed three dimensional finite element analyses on the cruciform specimens under elastic and creep conditions. Specimen finite element model is generated with MSC/Patran [3] and analytical calculations are conducted with MARC finite element code [4]. Results pertaining to this combined analytical and experimental study are reported and their impact on estimating the life of the component is evaluated.

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6176-58, Poster Session

On the material characterization of a composite using micro CT image based finite element modeling

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Novel techniques for generating robust and accurate meshes based on 3D imaging data have recently been developed which make the prediction of macro-structural properties of composite structures based on micro-structural composition straightforward. The accuracy of reconstructions is a particular strong point of these new techniques with geometric accuracy only contingent on image quality. Algorithms developed and used are topology preserving, volume preserving and multi-part geometric models can be handled straightforwardly. In addition to modeling different constituent materials as separate mesh domains, material properties can be assigned based on signal strength in the parent image thereby providing a way of modeling continuous variations in properties for an inhomogeneous medium. These new techniques have been applied to the analysis of a ceramic matrix composite which was micro-CT scanned and the influence of imaging parameters on both predicted bulk properties and localized stresses has been explored.

This paper, in addition to exercising the above technical schemes, will utilize the Computed Tomography (CT) as the NDE technique to characterize the initial matrix porosity's locations and sizes in various CMC test specimens. Further, the Finite Element method is applied to calculate the localized stress field around these pores based on the geometric modeling of the specimen's CT results, using image analysis and geometric modeling software, ScanIP/ScanFE [1]. The analyses will simulate experimental loading conditions where scanned specimens are

then tensile tested to a 0.07 % total strain to identify the matrix cracking locations in relation to the original pores. Finally, the calculated Finite Element [2, 3] localized stress risers are compared with the observed matrix cracking locations. This work it is expected to show that a FEA model based on an accurate 3D rendered model from a series of CT slices is an essential tool to quantify the effects of internal macroscopic defects of complex material systems such as Ceramic Matrix Composites (CMCs).

6176-19, Session 4

Time reversal method for damage detection of cracked plates in the medium frequency range: the case of wavelength-size cracks

Y. Pasco, J. Pinsonnault, P. Masson, P. Micheau, Univ. de Sherbrooke (Canada)

The use of time reversal methods for localization and characterization of damages in plates is usually combined with high frequencies guided waves in a local elastic wave propagation formulation. In such a situation pulses and echos may be clearly separated in time. As a consequence, the study of the diffracted field on a damage of which geometrical dimensions are large compared to the wavelengths used for wave propagation allow to consider the structure itself as “near infinite” because the modal behavior may not be established. However those high frequencies may not be required. In the presented approach, medium frequencies are used and boundary conditions need to be considered. The interest of this frequency range is in using lightweight signal processing devices limited to low data transfer rates as expected for in-flight fuselage skin inspections. This study focuses on the case of wavelengths which are in the order of the largest geometrical dimension of the cracks.

In the first part, a simple infinite plate is used to validate the concept of diagonalization of the time reversal operator for flexural wave propagation.

In the second part, a modelling tool is extended to describe the vibration behavior of pristine and damaged thin plates in the low and medium frequency range below 50 kHz. The proposed analytical model employs a Hierarchical Trigonometric Functions Set (HTFS) to characterize homogeneous plates with through cracks. To approximate the effect of a small crack in a plate for all combinations of classical boundary conditions, high order approximation functions are required. The proposed approach takes the advantage of the stability of the HTFS for these high orders.

A notable advantage of this model is that it does not require a dense uniform meshing of the plate, with a minimum of 10 nodes per wavelength, as most finite element models require. The time reversal concept introduced before is then applied to a finite plate with known boundary conditions. Experimental validation of the model is conducted in the time domain for pristine and cracked plate structures and is showing potential results for crack detection.

6176-20, Session 4

An improved technique for modal decomposition of a double-mode Lamb wave signal

K. Luangvilai, L. J. Jacobs, J. Qu, Georgia Institute of Technology

This study develops a technique to decompose a multi-mode, transient Lamb wave signal into individual Lamb mode signals. The previously-proposed technique (presented at the SPIE NDE conference 2005) showed an encouraging efficiency for numerically-simulated signals, but suffered when evaluating real experimental signals due to its high sensitivity to noise and experimental errors. The improved technique starts with the same assumption of known Lamb wave propagation characteristics (known propagation dispersion curves). However, a highly-strict signal model governing the development of the previously-proposed technique is relaxed to tolerate unavoidable presence of noises and errors, and the problem is re-formulated. For real experimental signals, some additional signal processing techniques are introduced in signal pre-conditioning. The entire implementation of the improved technique is first tested with simulated signals, and then applied to real experimental signals. The final results with real experimental signals are presented and discussed with additional improvements and extension to attenuated signals.

6176-22, Session 5

Impedance-based structural health monitoring of thermal protection systems

B. L. Grisso, D. J. Inman, Virginia Polytechnic Institute and State Univ.

Thermal protection systems on spacecraft are crucial for the survival of the vehicle during Earth reentry. The complex nature of thermal protection systems and extreme reentry temperatures and do not allow for easy access to monitor the condition of the external surface of the spacecraft. An active sensing system is proposed to interrogate the exterior of the surface and provide automated damage detection, diagnostics, and prognosis. Impedance-based health monitoring techniques utilize small piezoceramic (PZT) patches attached to a structure as self-sensing actuators to both excite the structure with high-frequency excitations, and monitor any changes in structural mechanical impedance. By monitoring the electrical impedance of the PZT, assessments can be made about the integrity of the mechanical structure. Components used the thermal protection have not previously been interrogated with the impedance method. In this study, structures are fabricated to represent typical thermal protections systems. The replicas are designed to simulate actual protection systems in use. Observations are made into the verification of the impedance method in effectively monitoring complex thermal protection systems from non-optimal sensor placement locations. The thermal protections systems are damaged in a way to represent typical damage mechanisms. The sensitivity of the impedance method to various types of damage in representative structures will also be discussed. Different operational conditions, including high temperatures, are also included in the experimentation. A small repair assessment evaluation will also be performed.

6176-23, Session 5

Structural health monitoring of an inflatable boom on simulated debris/meteorite impact

P. A. Tarazaga, D. J. Inman, Virginia Polytechnic Institute and State Univ.; W. K. Wilkie, NASA Jet Propulsion Lab.

Inflatable space structures are part of an emerging technology that could potentially revolutionize the design of large on-orbit satellites. These systems have advantages such as less mass, higher packaging efficiency, lower life cycle cost, simpler design with fewer parts, and higher deployment reliability. Since these systems are usually thin walled, orbital debris and meteoroids pose a considerable threat to the wellbeing of these systems. Such impacts would create punctures on the structure of varying sizes related to the size of the debris/meteorite. These impacts would penetrate the thin wall of the boom twice, once as it enters and once again as it leaves the structure. Being able to monitor the state of these satellites would be of great interest. To show the feasibility of such an idea an inflatable boom was equipped with a Macro-Fiber Composite (as a collocated sensor) and damage was simulated on the structure. To determine the extent of the damage sustained, impedance signatures were acquired before and after the damage for comparison.

6176-24, Session 5

Terahertz NDE for metallic surface roughness evaluation

R. F. Anastasi, E. I. Madaras, NASA Langley Research Ctr.

Metallic surface roughness in a nominally smooth surface is a potential indication of material degradation or damage. When the surface is coated or covered with an opaque dielectric material, such as paint or insulation, then inspecting for surface changes becomes almost impossible. Terahertz NDE is a method capable of penetrating the coating and inspecting the metallic surface. The terahertz frequency regime is between 100 GHz and 10 THz and has a free space wavelength of 300 micrometers at 1 THz. Terahertz radiation is generated and detected using optical excitation of biased semiconductors with femtosecond laser pulses. The resulting time domain signal is 320 picoseconds in duration. In this application, samples are inspected with a commercial terahertz NDE system that scans the sample and generates a data set of time-domain signals that are a function of the coating and backscatter from the metallic surface. Post processing is then performed in the time and frequency domains to generate C-scan type images that show scattering effects due to surface non-uniformity.

6176-25, Session 5

Structural health monitoring for insulation panels of LNG carriers using smart sensors

M. H. Kim, Y. J. Sohn, S. W. Kang, J. M. Lee, Pusan National Univ. (South Korea); S. Na, Korea Univ. (South Korea)

LNG (liquefied natural gas) is expected to play an increasingly important role in the global energy markets, and this initiated a trend to increase the capacity of LNG carriers and further development of the design technology for LNG tanks. LNG tanker of membrane type is covered with a primary metal alloy membrane and a composite secondary barrier incorporated in the insulation panels. One of technical issues associated with LNG carriers is the ability of the cargo containment system to withstand sloshing loads. Sloshing-induced impact load may cause

a critical damage on insulation panels.

The aim of the study is to investigate the dynamic failure initiation as well as the failure modes of insulation panels of LNG carriers. Insulation panels of LNG cargo tanks may include mechanical failures such as fatigue cracks as well as delaminations within the layers due to impact sloshing loads and fatigue loadings, and these failures may cause a significant decrease of the structural safety.

A structural health monitoring technique employing fiber optic sensors for the measurements of static, dynamic strain and damage initiation is developed for the structural integrity assessment of LNG carrier insulation system. For this purpose, a dry drop test facility was constructed for dropping a certain weight on the top of insulation panel test specimen in a repetitive manner to simulate the sloshing impact loads. The present research involves a study of the performance of embedded fiber optic sensors under condition of static and dynamic loading, when exposed to intact and damage conditions.

Fiber optic sensors have the advantage of being embedded inside of insulation panels. The measurement signal of embedded fiber optic sensor is used to calculate the strain distribution within insulation panels and is analyzed to identify the damage initiation. It has been observed that the presence of defects and delaminations produce noticeable changes in the strain measurement in a predictable manner. In addition, fiber optic sensors are used to measure static and dynamic strain variations with and without damage. It is expected that this study will be used as a fundamental study for the safety assessment of LNG insulation panels.

In addition, a new impedance-based structural health monitoring system employing piezoceramic transducers is developed with a special interest in applying the technique for detecting possible damages within the insulation panels due to sloshing impact. In particular, the impedance-based structural health monitoring technique that employs the coupling effect of piezoceramic (PZT) materials and structures is investigated. The test result from the study indicates that the impedance-based health monitoring technique can provide an effective mean for detecting damage on the structures.

6176-27, Session 6

A mixture of experts approach for SHM measurement processing

D. K. McNeill, Univ. of Manitoba (Canada)

One of the greatest challenged in deploying structural health monitoring (SHM) systems is the need to manage the continuous stream of measurements obtained from tens or hundreds of installed sensors. In a practical system the analysis of these measurements must be performed in an automated and robust manner and be completed in real-time. As the first stage in this process, a neural computing based novelty detection system has been developed which is capable of modeling the basic behaviour of a structure and subsequently isolating noteworthy measurements. In this article we examine the trade-off between the system's need to adapt to normal changes in a structures behaviour over the long-term, versus the need to maintain a reliable reference model so as to identify important events when they occur. It is demonstrated that extending the existing basic neural processing system, by introducing a 'mixture of experts' approach, can address the contradictory needs of adaptability and model stability. In addition, it is shown that this approach provides a means of incorporating detection of both short-term and long-term phenomena into a single integrated processing system.

6176-30, Session 6

A fusion approach to improve robustness and reduce ambiguity of damage detection results

Z. Duan, J. Hao, Harbin Institute of Technology (China)

Damage detection has been one of the core problems for structural health monitoring technology. Many damage detection techniques have been proposed in vast amount of literature so far, however none of them has emerged as a universal method with acceptable reliability. Every damage detection method has its merits and uniqueness from the theoretical background it's proposed, the data it utilizes, and the techniques it's implemented. The results of individual damage detection method are also mostly influenced by the noises in the data, and the information dropped (or information utilized) in the extraction of damage sensitive parameters, etc. Those factors bring low robustness and low creditability to an individual damage detection method. Besides, for some damage detection methods, the results are usually so ambiguous that it's hard to decide if damage occurs.

A fusion approach is proposed to improve the robustness and reduce ambiguity of damage detection technique. The idea of this approach is to take advantage of different damage detection results by fuse them with data fusion technology. In this paper, Multiple Damage Location Assurance Criterion (MDLAC) method, Frequency Change Damage Detection Method (FCDDM) and Wavelet Packet Component Energy (WPCE) damage detection method are introduced. Then, the Dempster-Shafer evidence theory is introduced, and technique to fuse results from individual method is presented. Finally the proposed approach is experimentally studied by a five-story steel frame structure, and a more robust and clear damage detection result is achieved.

6176-31, Session 6

Monitoring of cable tension of cable-stayed bridge using wireless sensor network

H. Li, J. Ou, Harbin Institute of Technology (China)

Bridge cables are used as critical structural components for cable-stayed bridges. Therefore, the on-line monitoring of the stayed cables' tension of the cable-stayed bridges can provide vital information to assess the global health of the bridges. However, conventional monitoring systems employ cables for measurement transfer, and collect data at a single server for centralized processing. A major drawback of these systems is their installation time and costs can be very high. In this paper a new monitoring system based on wireless sensor network techniques for measurement of cable tensions are introduced. The system is consisting of a base station and an array of wireless accelerometer sensors that can be easily installed on the bridge cables. The hardware and software of the system are investigated and described. The proposed system is instrumented on a newly constructed Sifangtai cable-stayed bridge over the Song Huang Jiang River, Harbin, China. The natural frequencies, mode shapes, and modal damping ratios of the cables to evaluate the cable tensions were calculated by the system. The preliminary results show that the proposed system is an effective tool for on-line monitoring the stayed cable tension of cable-stayed bridges.

6176-32, Session 6

Reliability analysis of the upper anchorage of a cable-stayed bridge using a probabilistic structural model

D. Samayoa, Instituto Politécnico Nacional (Mexico); F. J. Carrión, Instituto Mexicano del Transporte (Mexico); A. Balankin, Instituto Politécnico Nacional (Mexico); A. Lopez, Instituto Mexicano del Transporte (Mexico)

This work describes the experimental and theoretical approach used for the development of a structural reliability model for the upper anchorage of a cable-stayed bridge. Experimental and field analysis are used to establish the statistical models for uncertainty in material constitutive laws, fracture toughness, external loads (traffic and wind), and material defects (inclusions and pores). A standard reliability method is used for the evaluation of probabilistic characteristics of parameters and for the failure probabilities. Finite element analysis is used within two levels; the first level considers the model of the whole bridge to calculate the loads on the anchorages under different external load conditions. The second level considers the detailed model for the anchorage to calculate stresses on critical points. A particular semi-empirical model is used to analyze fatigue and to predict structural life. The reliability model is evaluated through the simulation of different scenarios of loads and wind conditions.

6176-33, Session 6

Assessment of tendon duct integrity in concrete through ultrasonic imaging

K. J. Langenberg, K. Mayer, Univ. Kassel (Germany)

Once tendon ducts in concrete have been located through the steel reinforcement grid with electromagnetic waves (with a ground probing radar) the next step consists of an integrity check, i.e. the indentification of potential grouting defects. This can be achieved with elastic waves in the ultrasonic frequency regime. Since the propagation properties of elastic waves, be it either pressure or shear waves, are highly determined by the inhomogeneity of concrete, in particular by air inclusions, it is of tremendous importance to understand the interaction of ultrasound with grouting holes in detail. Therefore, we utilize a powerful simulation tool - EFIT for Elastodynamic Finite Integration Technique - to study this interaction on the basis of synthetic data. These are obtained in 2D as well as in 3D simulating the A1220 point contact transducer either in a pressure or shear wave mode. It turns out that the backscattered signal phase is rather sensitive to the presence or absence of grouting defects.

The recording of pulsed scattered ultrasonic data within a synthetic aperture on the concrete surface allows for the application of imaging algorithms. We have developed a 3D diffraction tomographic scheme (FT-SAFT for Fourier Transform Synthetic Aperture Focusing Technique) which operates in quasi-realtime due to

the sole utilization of Fourier transforms. We apply FT-SAFT to the above-mentioned synthetic data as well as to experimental data obtained from a test specimen. It turns out that the superposition of the calculated 3D image with the phase information clearly identifies grouting defects. First results obtained from a highway bridge near Vienna in Austria will also be reported.

6176-35, Session 6

Structural health monitoring of PC structures with distributed HCFRP sensors

C. Yang, Z. Wu, Ibaraki Univ. (Japan)

The authors have done a series of investigations on the development of a novel type of hybrid carbon fiber reinforced polymer (HCFRP) sensors. The composite sensors, composed of three types of carbon fibers high strength (HS), middle modulus (MM) and high modulus (HM) carbon fibers, are featured with a broad, stage-based and distributed sensing function. Moreover, the sensors are durable and highly resistive to corrosion due to the excellent physico-chemical properties of carbon fibers. Therefore, they are believed to be suitable for the sensing requirements in civil engineering. In this paper, the structural health monitoring (SHM) function of PC beams are studied with the application of HCFRP sensors. Two types of HCFRP sensors without and with pretreatment are mounted on PC tendon, steel bar, and compressive and tensile sides of the beam to monitor the strain, yielding of steel bar, initiation and propagation of cracks, respectively. The sensor without pretreatment is sensitive after a strain of about 3,000m suitable for monitoring the health of PC tendons; while the sensor with pretreatment is sensitive before a strain of 1,000m suitable for measuring the strain and monitoring the initiation and propagation of cracks. As designed, according to the electrical behavior of the HCFRP sensor and the mechanical state of the PC structures, the monitoring of the PC structures can be divided into several stages due to the gradual ruptures of different types of carbon tows such as HM and MM carbon tows. In stage I before the yielding of rebars or initiation of concrete cracks, there are no macro-ruptures of carbon fibers, and the electrical resistance changes slowly in proportion to the applied load. In stage II where the rebars begin to yield, the HM carbon fibers are designed to rupture, which results in a sudden and obvious jump in electrical resistance. Thus, the yielding of the rebars can be clearly monitored by measuring the jump in electrical resistance. Stage III corresponds to the strain-strengthening stage, where the gradual ruptures of MM carbon fibers can further enhance the fractional increase in electrical resistance. At the end of this stage, the sudden rupture of MM carbon fibers can also result in a sudden and finite jump in electrical resistance. And the strain softening corresponds to stage IV, during which the HS carbon fibers begin to rupture. It is shown that the initiation of crack in concrete can result in a sudden jump in electrical resistance of 5.6% and a higher increasing rate. After the yielding of steel bars, the electrical resistance increases quickly with load. The four-point bending experiments reveal that the strain of PC tendons, yielding of steel reinforcing bars and initiation of cracks can be effectively monitored with the application of HCFRP sensors.

6176-36, Session 7

Underwater application of structural health monitoring at Fairview Cove container terminal

J. P. Newhook, Dalhousie Univ. (Canada); V. Limaye, MacDonnell Group Limited (Canada); J. Gaudet, Dalhousie Univ. (Canada); D. Carter, Halifax Port Authority (Canada)

An often overlooked application for structural monitoring technology is the monitoring of the 'health' of structures during construction and rehabilitation activities. For many structures, unique loadings are created during the construction phase that do not exist at any other time during the life of the structure. The same is true for many rehabilitation activities. In addition, the nature of the construction or rehabilitation may create conditions of instability that would not otherwise exist in the structure. Monitoring the 'health' of the structure in this context refers to an assessment of whether the loading or change of boundary conditions has had an adverse effect on the structure. Indeed, the monitoring may be even more critical if it is foreseen that the changes may lead to an unsafe condition or imminent collapse during construction. This paper will describe one such project in which SHM techniques were used to assess the impact of a unique rehabilitation scheme on the stability and serviceability of an existing structure.

The MacDonnell Group Consulting Ltd (MGCL) was retained by the Halifax Port Authority to design and specify a monitoring system for the Fairview Cove Container Terminal at Halifax, Nova Scotia. The terminal originally had a water depth of 14 m. The Port Authority of Halifax decided to increase the water depth by three metres at the terminal to handle the anticipated traffic of newer post-Panamax vessels with larger drafts. The existing terminal had rock-filled concrete cribs (caissons) resting on a rock mattress. The deepening work included; a) driving of sheet piles along the cribs, b) anchoring of sheet piles to the bottom edge of the cribs, and c) dredging out three meters of the existing sea floor along the face of the sheet piles. The Port Authority wished to monitor the effects of deepening operations on the cribs, sheet piling, and the anchor bolts. A monitoring scheme comprising vibrating wire strain gauges, and two different types of fibre optic sensors, all capable of performing under 14 m of water, was designed, installed, and commissioned in January 2005. This paper describes the process of design, installation and operation of the system, and discusses the interpretation of the acquired data. This is the first known underwater application of SHM to marine structures.

6176-37, Session 7

Identifying damage on a bridge deck using vibration-based damage indices derived from limited measurements

A. B. Siddique, March Consulting Associates Inc. (Canada); L. D. Wegner, B. F. Sparling, Univ. of Saskatchewan (Canada)

Vibration-based damage detection (VBDD) methods use changes to the dynamic characteristics of a structure (primarily its natural frequencies and mode shapes) to detect the presence of damage and determine its location. Numerous VBDD indices have been proposed. Earlier studies have shown that several of these can be used to quite reliably detect and locate damage on bridge decks with a relatively high level of precision provided the superstructure is heavily instrumented. For example, on a slab-on-girder bridge superstructure, when every girder line is instrumented with an array of closely spaced sensors to measure flexural mode shapes, damage on the deck will generally produce a distinct spike in the VBDD indices near the damage location, particularly if the damage is not located too near a support. These spikes are generally highly localized, however, which means that locating damage becomes much more challenging when fewer measurement points are used.

Usually, it is not feasible to close a bridge to traffic when conducting tests. Limited access means that measurements can only be made along a few lines-perhaps only along barrier walls or medians. In such cases, the spikes in the VBDD indices are generally not apparent unless damage happens to be located in the vicinity of an instrumented line. Despite this, it may be possible to use the spatial patterns of the VBDD indices derived from the more limited measurements to at least determine whether damage is present, and possibly to obtain a general idea of its location. This would constitute a Level 1 structural health monitoring system. If such a system is able to reliably determine that damage is present, a more intensive vibration measurement program, perhaps involving a short-term closure of the structure, could be subsequently implemented to precisely locate the damage.

This paper focuses on interpreting the spatial patterns of VBDD indices derived from limited data with the goal of determining whether the presence of damage can be reliably detected. The structure used as the basis for this study was a two-span, slab-on-girder, integral abutment bridge located in Saskatoon, Canada. The dynamic response of the bridge under ambient traffic loading has been measured on several occasions using temporarily installed accelerometers. A detailed finite element (FE) model was then developed and calibrated to match the natural frequencies and mode shapes acquired from measured data. This model was used to simulate the dynamic response of the bridge as various states of small-scale damage were induced at various locations on the deck. The variation of VBDD indices along three longitudinally oriented lines was studied to identify patterns that would allow a reliable determination of whether damage is present and in what region of the bridge it might be located. The influence of damage size, location, and measurement noise was considered.

6176-38, Session 7

Laboratory and field performance of FOS sensors in static and dynamic strain monitoring in concrete bridge decks

B. Benmokrane, Univ. of Sherbrooke (Canada) and ISIS Canada Research Network (Canada); S. El-Gamal, A. S. Debaiky, A. El-Ragaby, E. El-Salakawy, Univ. of Sherbrooke (Canada)

There is a growing need for designing and constructing innovative concrete bridges using FRP reinforcing bars as internal reinforcement to avoid the corrosion problems and high costs of maintenance and repair. For efficient use and to increase the life time of these bridges, it is important to develop efficient monitoring systems for such innovative structures. Fabry-Perot and Bragg fibre optic sensors (FOS) that can measure the strains and temperature are promising candidates for life-long health monitoring of these structures. This article reports laboratory and field performance of Fabry-Perot and Bragg FOS sensors as well as electrical strain gauges in static and dynamic strain monitoring in concrete bridge decks.

The laboratory tests includes tensile testing of glass FRP bars and testing of full scale concrete bridge deck slabs reinforced with glass and carbon FRP bars under static and cyclic concentrated loads. The fields tests includes static and dynamic testing of two bridges reinforced with glass and carbon FRP bars. The obtained strain results showed excellent agreement between the different gauges.

6176-39, Session 7

Evanescent field fiber Bragg grating sensors for detecting aging in civil infrastructure

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Fiber Bragg grating sensors are one of several fiber optic sensor technologies currently being used in structural health monitoring systems. When the effective refractive index of a fiber Bragg grating is changed by external chemical variations (e.g. pH), the wavelength at which incident light experiences a maximum reflection from the grating will correspondingly shift. Therefore, the detection system collects the light spectra from the grating and converts the wavelength shift into a chemical change.

The sensitivity of a fiber Bragg grating to chemical changes increases when the grating is polished on one side. This side-polishing technique enables the Bragg grating to preserve a greater portion of its mechanical strength as compared with other techniques such as chemical etching. In this work, we will utilize side-polished fiber Bragg grating sensors that are centered at a 1542 nm wavelength and have cladding thickness values from 3-5 micron. We aim to study the response of these sensors to small refractive index changes. Since previous work on fiber Bragg grating sensors has shown that the peak wavelengths can be measured with 3 pm repeatability, we estimate that a 0.0001 refractive index change will be observed with these sensors. Consequently, side-polished fiber Bragg grating sensors show great promise for early detection of aging in civil infrastructure.

6176-42, Session 7

A study on the application of CB-filled cement-based composites as a strain sensor for concrete structures

H. Xiao, H. Li, Harbin Institute of Technology (China)

No abstract available

6176-44, Session 8

Structural health monitoring of the Gröndals Bridge in Sweden

A. Hejll, B. Täljsten, A. Carolin, Luleå Univ. of Technology (Sweden)

No abstract available

6176-45, Session 8

Structural health monitoring of a concrete bridge in Sweden

O. Enochsson, B. Täljsten, T. Olofsson, Luleå Univ. of Technology (Sweden)

No abstract available

6176-46, Session 8

Aplication of draw-wire displacement sensors on structural health monitoring of Jiangyin bridge

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The original structural health monitoring system of Jiangyin Bridge was designed by British Jams Scott Limited, and was constructed by British Strainstall Engineering Serviced Limited. Recently, the old system can not operate normally owing to the failures of partly sensors and the damage of data acquisition systems. The draw-wire displacement sensors to monitor the longitudinal displacement of the main girder of Jiangyin Bridge were introduced in the upgrading projects of the structural health monitoring system. The draw-wire displacement sensors were placed at the two ends of the main girders. The longitudinal displacements at the end of the main girder are being real-time measured when the draw-wire moves with the main girder. The sensors were installed on the cushion caps at the southern and northern ends of the main girder. One sensor was installed at each eastern and western side of per cushion cap, so the total sensors were four. The signal of the sensors was transmitted through the communication cables. The sampling frequency is 50Hz. The displacement changes between the two ends of main girder and the synchronism of displacement at the eastern and western sides are acquired by analyzing statistically the measured data. On the accident of the impact by ship, the displacement response and the excited status of the bridge were collected to evaluate the damage of the structure. The research results show that the variation value of the daily displacement of the main girder is small but the frequency of the movement is high, the displacement at the eastern and western sides has a good synchronism. The high-frequency vibration of the structure occurred after the impact of ship but the amplitude of vibration was relatively smaller than the daily displacement variation, so the impact has small influence on the structure and the structural rigidness of the main girder has no obvious deterioration after six-year services.

6176-47, Session 8

Application of distributed long-gage fiber optic sensors in structural assessment for reinforced concrete beams

S. Li, Z. Wu, Ibaraki Univ. (Japan)

No abstract available

6176-48, Session 8

Full implementations of structural health monitoring systems for long-span bridges and large-span domes

H. Li, J. Ou, Harbin Institute of Technology (China)

No abstract available

6176-49, Session 8

Sensor strain detection and localisation with the distributed Brillouin sensor based on phenomenological signal processing approach

F. Ravet, X. Bao, L. Zou, V. Kalosha, Q. Yu, L. Chen, Univ. of Ottawa (Canada)

No abstract available

6176-50, Session 8

Research and practice of intelligent sensing technologies in civil structural health monitoring in the mainland of China

J. Ou, Harbin Institute of Technology (China)

No abstract available

6176-51, Session 8

In-situ health monitoring of reinforced concrete using piezoceramic transducers

X. Zhao, Dalian Univ. of Technology (China)

A smart sensor system was developed to monitor the possible cracks of structure in this paper. Piezoelectric material which has the advantages of direct and converse piezoelectric effect was chosen to be transducer. Since piezoceramic can produce relatively large voltage with little power, it was applied to be stuck on the surface of structure where the most possible damage might occur. Under electrical excitation piezoceramic actuator could generate elastic wave which could propagate in the structure. The structure which the piezoceramic transducers monitored was a reinforced concrete frame-shear wall of scale 1:4 under simulation earthquake. When the structure is in plastic yield stage, the transducers began to do effect. That is, when the earthquake change from 0.2g to 1.0g, the actuator start to work. Damage index was defined by employing wavelet packet theory and root mean square deviation method. The result indicates that piezoelectric material is adapted to effectively monitor micro-damage of civil structure.

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6177-01, Session 1

Autonomous health monitoring of a stiffened composite plate

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The paper presents a unified computer assisted automatic damage identification technique based on a damage index, associated with changes in the vibrational and wave propagation characteristics in damaged structures. An improved ultrasonic and vibration test setup consisting of distributed, high fidelity, intelligent, surface mounted sensor arrays is used to examine the change in the dynamical properties of realistic composite structural components with the appearance of damage. The sensors are assumed to provide both the low frequency global response (i.e., modal frequencies, mode shapes) of the structure to external loads and the (local) high frequency signals due to wave propagation effects in either passive or active mode of the sensor array. Using the initial measurements performed on an undamaged structure as baseline, the damage indices are evaluated from the comparison of the frequency response of the monitored structure with an unknown damage. The technique is applied to identify impact damage in a woven stiffened composite plate that presents practical difficulties in transmitting waves across it due to scattering and other energy dissipation effects present in the material and the geometry of the structure. Moreover, a sensitivity analysis has been carried out in order to estimate a threshold value of the index below which no reliable information about the state of health of the structure can be achieved. The feasibility of developing a practical Intelligent Structural Health Monitoring (ISHM) System, based on the concept of "a structure requesting service when needed," is discussed.

6177-02, Session 1

Monitoring schemes for the observation of directional solidification in the International Space Station

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Monitoring schemes for the detection of the solid liquid interface during directional solidification have been developed including electronic equipment for the Material Science Laboratory(MSL) of the International Space Station (ISS). The developed schemes are presented and demonstrated. Special signal and data processing suitable for automatic monitoring, on board signal averaging, and operation under limited data transfer conditions are discussed. The achievable resolution in the micrometer regime, as well as post-experimental processing and evaluation for high resolution monitoring are presented and exemplified for typical applications.

6177-03, Session 1

Challenges in detecting damage in the presence of microstructural inhomogeneties in a friction stir welded aluminum alloy for reusable cryotanks

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Structural health monitoring approaches are being developed for continuous examination of the health of cryotanks for space-access in real-time. The reusable cryotanks will be manufactured using friction stir welding technology and the reusability of these tanks for multiple-missions requires weld and microstructural integrity. The weld contains not only multiple interfaces but also a variety of microstructures and the challenge is to develop a comprehensive NDE-based health monitoring capability that will detect damage and monitor it's progression in the presence of the above microstructural inhomogeneities. In order to understand the microstructure several microscopic and NDE-based techniques were used including x-ray diffraction, eddy current and acoustic microscopy. Acoustic wave propagation across the weld boundaries was visualized using laser interferometry. Elastic wave propagation techniques were used to evaluate the detectability of intentionally introduced microstructural and mechanical damage.

6177-04, Session 1

Identifying delamination in an experimental composite UAV wing subject to ambient gust loading

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Vibration-based structural health monitoring has largely considered applied excitations as the primary means of inducing structural vibration. Here we consider how ambient vibrations might be used to assess the level of damage in a composite UAV wing. The wing consists of a foam core and a carbon fiber skin. We subject the wing to various amounts of impact damage in order to cause internal delaminations. The wing is then excited using a gust loading profile in an effort to simulate the loading the wing expects to see in flight. We then use probabilistic description of the structure's dynamics to assess the appearance of damage-induced changes.

The approach focuses on detecting the presence of nonlinearity due to the damage and is capable of making the diagnosis in the absence of a representative baseline data set from the "healthy" wing.

6177-05, Session 1

Fundamental ultrasonic wave propagation studies in a model thermal protection system

T. Kundu, The Univ. of Arizona; K. v. Jata, Air Force Research Lab.

A model thermal protection system (TPS) was designed by bonding ceramic porous tiles to an aluminum alloy plate. One of the goals of the present work was to investigate the potential of detecting simulated defects using guided waves. Simulated defects consisted of delaminations, cracks and voids, and these were introduced into the porous tiles during the fabrication of the TPS. Guided wave propagation studies were conducted using the pitch-catch approach, while changing the angle of strike and the frequency of the transducer excitation. The receiver was placed at a distance so that only the guided waves were received. As expected the delamination defect could be conclusively detected, however imperfect bond between the tiles and the bonding material and/ or substrate was interfering with the detection of the simulated cracks and void-defects.

6177-06, Session 2

Application of time-reversal guided waves to field bridge testing for baseline-free damage diagnosis

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In our ongoing research related to reference-free damage diagnosis, we are developing a new concept of nondestructive evaluation methodology. The uniqueness of this baseline-free diagnosis lies in that certain types of damage can be identified without direct comparison of test signals with previously stored baseline signals. By removing dependency on the past baseline data, we intend to minimize false positive indications of damage that might take place due to varying operational and environmental conditions of in-service structures. This baseline-free diagnosis technique is developed based on the concept of a time reversal process. Based on the time reversal process, an input signal at an original excitation location can be reconstructed if a response signal obtained from another point is emitted back to the original point after reversed in a time domain. Here, the basis premise for damage diagnosis is that the time reversibility breaks down when a certain type of defect such as nonlinear damage exists along the wave propagation path. Therefore, certain types of defects can be sensed by examining the deviation of the reconstructed signal from the original input signal. In particular, the feasibility of crack detection will be investigated using data measured from actual field tests of fracture critical bridge structures in Pennsylvania.

6177-07, Session 2

Plate damage identification using up-converted chaotic excitations and time-reversal acoustics

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Lamb waves have been widely used as an efficient means of detecting damage in

plate-like structures. Numerous signal-processing techniques are available for evaluating and processing measured Lamb waves for damage identification. In this study, we investigated the use of a novel excitation that is created by frequency conversion of a standard Lorenz chaotic signal (AM chaos) into the acoustic regime. We launch this wave using an MFC actuator, detect it with another MFC sensor, time-reverse it, and relaunch back to the original MFC. Pre- and post-state space reconstructions may be compared to generate error metrics indicative of damage paths. This approach will be compared to traditional methods of Lamb wave generation using standard tone burst waveforms. Furthermore, a computational model of Lamb wave propagation was used to help interpret experimental results from an aluminum plate with piezoelectric patches used as sensor/actuators.

This paper summarizes considerations needed to design such damage identification systems, experimental procedures and results, and additional issues that can be used as a guideline for future investigation.

6177-08, Session 2

The use of time-reversal methods with Lamb waves to identify structural damage in a pipeline system

A. Thien, A. Puckett, G. Park, C. R. Farrar, Los Alamos National Lab.

Harsh environmental and operating conditions often leave pipeline systems prone to cracks, corrosion, and other aging defects. If left undetected, these forms of damage can lead to the failure of the pipeline system, which may have catastrophic consequences. Most current forms of health monitoring for pipeline systems involve nondestructive evaluation (NDE) techniques. These techniques often require a pipeline system to be taken out of operation at regularly scheduled intervals so that a technician can perform a prescribed NDE measurement. Such a measurement also requires direct access to the pipe¡¯s exterior or interior surface. This access may require excavation if the pipe is underground and the removal of insulating layers when present. This research proposes the use of Macro-fiber composite (MFC) actuators for damage detection in pipeline structures. Because MFC actuators are durable and relatively inexpensive, they can be permanently bonded to the surface of a pipe during installation. Therefore, measurements for damage detection can be performed at any time, even while the system is still in operation.

The time reversal methods use the propagation of Lamb waves to evaluate the structural health of a pipeline system. A burst waveform is used to excite Lamb waves in a pipe at an initial location using an array of MFC patches. The measured response at the actuation location is reversed in time and then used as the excitation signal at the second location. The initial excitation signal is then compared to the final response signal. The performance of the time reversal methods was compared to the traditional methods of Lamb wave propagations using standard tone burst waveforms.

This paper summarizes considerations needed to design such damage identification systems, experimental procedures and results, and additional issues that can be used as a guideline for future investigation.

6177-09, Session 2

Scattering of ultrasonic waves by cracks and inclusions in plates immersed in a fluid

S. Banerjee, T. Kundu, The Univ. of Arizona

In the field of Non-Destructive Evaluation (NDE), the inspection of plate structures is a common place. To detect cracks and inclusions in a plate the wave scattering by such anomalies needs to be investigated and is done in this paper. The elastic wave scattering by horizontal cracks is studied here. The analysis is carried out by a newly developed technique called Distributed Point Source Method or DPSM. DPSM is a semi-analytical technique that is different from the Finite Element Method (FEM) or the Boundary Element Method (BEM) and can be used to efficiently model the ultrasonic field (stress or pressure, velocity and displacement) generated by ultrasonic pressure transducers in different problem geometries. The objective of this paper is to present the necessary theory for modelling diffraction and scattering of guided waves in a solid plate when the transducers of finite dimension are inclined at critical angles corresponding to different Lamb wave modes. Results are presented showing the diffracted field patterns for various Lamb wave modes in cracked aluminum plates immersed in water.

6177-10, Session 2

Modeling wave propagation in damped waveguides of arbitrary cross-section

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Ultrasonic guided waves are an effective tool for Structural Health Monitoring (SHM) applications requiring large inspection ranges and high sensitivity to small discontinuities. The knowledge of the dispersive behavior of these waves, including velocity, attenuation and cross-sectional mode shapes, is important to design and use an effective SHM system.

This paper deals with a Semi-Analytical Finite Element (SAFE) method for modeling guided wave propagation in structures of arbitrary cross-section. The method simply requires the finite element discretization of the cross-section of the waveguide, and assumes harmonic motion along the wave propagation direction. The general SAFE technique is extended to account for viscoelastic material damping by allowing for complex stiffness matrices for the material. The dispersive solutions are obtained in terms of phase velocity, group velocity (for undamped media), energy velocity (for damped media), attenuation, and cross-sectional mode shapes. The proposed SAFE formulation is applied to several examples, including anisotropic viscoelastic layered plates, composite-to-composite adhesive joints and railroad tracks.

6177-11, Session 3

Crack detection in a wheel end spindle using wave propagation via modal impacts and piezo actuation

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This research demonstrates two methodologies for detecting cracks in a metal spindle housed deep within a vehicle wheel end assembly. First, modal impacts are imposed on the hub of the wheel in the longitudinal and radial directions to produce broadband elastic wave excitation spectra in those directions out to 7000 Hz. The response data on the flange is collected using 3000 Hz and 10000 Hz bandwidth accelerometers with different sensitivities. It is shown using frequency response and wavelet analysis that the crack filters waves beyond 1500 Hz and amplifies vibration amplitudes below 500 Hz. Experiments on wheel assemblies mounted off and mounted on the vehicle are performed to demonstrate that the modal impact method can be used to nondestructively evaluate cracks of varying depths despite sources of variability including the half shaft angular position relative to the non-rotating spindle.

Second, an automatic shear mode, pinching actuator is utilized to excite the wheel hub as well as the spindle flange with a swept sine signal extending from 10 kHz to 20 kHz. High-frequency, low profile accelerometers are then utilized to measure the response on the flange. It is demonstrated using wavelet analysis that the crack filters waves traveling from the hub to the flange. It is also demonstrated that the crack reflects waves traveling from the flange out towards the crack.

A simple finite element model is used to interpret the experimental results.

Challenges discussed include variability from assembly to assembly, the variability in each assembly, and the high amount of damping present in each assembly due to the transmission and other components in the wheel end. A two-channel measurement system with a graphical user interface for detecting cracks using these methods will be demonstrated at the conclusion of the talk so that the procedural steps required to ensure that operators properly perform the test can be addressed.

6177-12, Session 3

Wireless active sensor paradigm for actuation within smart structures

Y. Wang, Stanford Univ.; J. P. Lynch, Univ. of Michigan; K. H. Law, Stanford Univ.

In recent years, there has been a keen interest in the development of wireless sensing technology for monitoring civil structures. In many respects, wireless sensors represents a significant paradigm shift in how structural monitoring systems are designed and utilized. In particular, wireless sensors not only allow for data acquisition, but also offer opportunities to locally process measurement data. Past studies have explored the use of wireless sensors' computational resources for damage detection and system identification analyses. However, the wireless sensor largely remains a passive sensing technology with no opportunity to interact with the structures in which they are installed. In this study, a wireless sensing unit is proposed for the role of data collection, signal processing and actuation. Actuation allows the wireless sensor to have direct interaction with the structure it is installed. The wireless active sensing unit is designed to issue a variety of voltage command signals in real-time (100 kHz). The current voltage range spans from -5 to 5 V allowing it to command devices such as active sensors (e.g. PZT pads) as well as structural control actuators (variable dampers). A key element of the study is the illustration of the wireless active sensing unit upon a laboratory shaking

table; wireless active sensors are used to sense structural response, calculate control forces and issue actuation commands to the shaking table actuator.

6177-13, Session 3

A low-cost off-the-shelf FGPA-based smart wireless sensing unit

C. Kapoor, T. L. Graves-Abe, J. Pei, Univ. of Oklahoma

To continue with the development of a wireless sensing unit built upon an off-the-shelf FPGA development board presented by the authors at SPIE 2005, this paper outlines a further effort consisting of embedding on-board computations, simulation and validation of the FPGA-based wireless sensing unit that is able to collect, process and transmit data. This research supports the concepts of decentralized wireless sensor networks and local-based damage detection, where individual wireless sensor nodes are capable of performing intricate tasks and can eventually transmit the processed results. An FPGA-based hardware platform is thus looked upon as a major contender for performing this function in a proficient manner.

Throughout this research, the principal design complexities, in terms of both hardware and software development, are kept to a minimum. Development cycle and monetary cost of the hardware are other major considerations for this research. Data processing functions including windowing, Fast Fourier Transform (FFT), peak detection, are implemented into the selected FPGA, when limitations of different design options are explored to yield a solution that optimizes the resources of the selected FPGA. Numerical simulations and laboratory validations are carried out to scrutinize the operations and flexibility of the design.

6177-14, Session 3

Integrating monitoring and inspection with attached ultrasonic transducers

T. E. Michaels, J. E. Michaels, Georgia Institute of Technology

Ultrasonic methods are widely applied to the nondestructive evaluation of critical structural components during both the manufacturing process and subsequent field inspections. The field inspections often require expensive teardown in order to access the back surfaces of critical components. Active ultrasonic methods are also a subject of ongoing research for the monitoring of structural health whereby transducers are permanently attached to a structure and signals are monitored to detect changes caused by structural damage. This paper presents a methodology for effectively combining ultrasonic inspection and monitoring. During the monitoring phase, detection and localization of possible damage is demonstrated on metallic and composite plate specimens using attached transducers. This detection phase is followed by demonstration of a new inspection method referred to as acoustic wavefield imaging (AWI) which utilizes the attached transducers as sources and a single externally scanned air-coupled transducer as a receiver. The acoustic wavefield images are useful for both checking the viability of the attached transducers and quantifying the extent of structural damage. The AWI method approaches the sensitivity of conventional through transmission ultrasonic methods but does not require access to both sides of structural components. Thus, it is very well suited for rapid field inspection of structural assemblies.

6177-15, Session 3

Detection of debonding in a tile-based thermal protection system via change in stiffness using continuation methods

A. Shukla, Miami Univ.; K. Jata, Air Force Research Lab.

Thermal protection system is a critical component of a space vehicle and is essential for safe re-entry into the atmosphere. The loss of stiffness in tile based thermal protection system is an essential mode of damage and has lead to loss of a space vehicle due to excessive aero-dynamic heating during re-entry. The inherent nonlinear nature of the coupling of these tiles with the space vehicle body is well-known. This paper explores this nonlinear coupling and proposes a method based on continuation analysis of the nonlinear model to detect and track this damage. This model was first proposed by Luo and Hanagud (1998). This paper extends this model to a multi-degree-of-freedom nonlinear system. White, Adams and Jata (2005) used model analysis to conduct system identification and damage identification on a similar system using method of virtual forces. The present research extends this work by utilizing continuation methods to estimate the presence and degree of damage. Parametric studies are also conducted to study the effect of changes in mass on the detection of change in stiffness using the proposed method.

6177-16, Session 3

Organic strain sensors for structural state monitoring

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Organic strain sensors for structural state monitoring are investigated in this work. This MACROELECTRONICS technology is directed towards reliable high-density distributed sensors on flexible substrates that can be seamlessly integrated into aircraft structures such that structural state monitoring can be achieved. This technology will ultimately support structural health monitoring as well as enable feedback control for COGNITIVE AIRCRAFT applications—where distributed sensor data is algorithmically selected and post-processed in order to provide structural state information. The focus of this paper is development of organic strain sensors which are expected to be central to enhancing the capabilities of aircraft by providing the means for measuring static and dynamic state information for both structural health and usage monitoring. Thin film transistors (TFTs) as they interface with the strain sensors will also be discussed.

A significant concern about inorganic semiconductor strain sensors (ungated uC-Si and gated a-Si:H strain sensors), and even metal resistor sensors, fabricated on flexible substrates is the large stiffness mismatch between the sensor element and the substrate. The inorganic materials traditionally used posses high a Young's modulus (~200GPa) compared to the much lower Young's modulus of the currently investigated organic substrates (~5 GPa). Unique to this study is the investigation of novel organic strain sensors that are designed to match the mechanical properties (such as elastic modulus) of flexible substrates so as to avoid significant sources of error associated with property mismatch to flexible materials. Preliminary results demonstrate that these sensors are small (12 to 60 mil gage length), thin (<1 micron), posses gage factors between 10 to 24, and sensitivities of approximately 75 mV‰. To be sure, strain sensor sensitivity may be impacted by non-uniformities introduced by inorganic sensor islands on an organic substrate. In some cases stress concentration at the edges of inorganic structures may also lead to non-reversible plastic deformation of the organic material and problems with sensor reproducibility. Although current strain sensor development has improved compared to initial devices, the currently doped organic semiconductor resistivity is still undesirably large (~10^6 Ω-cm); however work continues to further optimize doping and recently ~10^2 Ω-cm has been achieved using a tetracyanoquinodimethanide (TCNQ) - a pentacene co-evaporated mixture. This paper will compare organic strain gages with inorganic semiconductor and metal foil strain gauges.

The specific research addressed in this paper is part of a larger MACROELECTRONICS for COGNITIVE AIRCRAFT collaborative effort where other technologies such as energy-harvesting for self-powering, wireless transmission, prognostics/diagnostic algorithms, large-scale solution processing and nanotechnologies may also be integrated together for a complete solution.

6177-17, Session 3

Damage detection using an active/passive structural neural system

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Although many different approaches have been proposed for Structural Health Monitoring (SHM), presently there are not many applications of SHM systems. The reason SHM has not been put into application on a wide scale is because the proposed methodologies are expensive and complex bulky instrumentation is required to detect small damage on large structures. As an example, it could become impractical based on cost, weight, complexity, and reliability to instrument an aircraft with a sufficient number of conventional point sensors to detect small damage. Typical SHM methods use wave propagation which is an important tool for damage detection. While it is known that the wave propagation dispersion curves for a flat plate are very simple, as the structural geometry becomes complicated these dispersion curves become complex and it is difficult to analyze and predict the location of damage. A simple approach for damage detection is needed that works on structures that have complex geometry and high feature density. In this paper a Structural Neural System (SNS) is proposed that requires only one channel of data acquisition to predict the location of damage irrespective of the large number of sensors used in the structural health monitoring network.

Figure 1(a) shows the architecture of the SNS. Each red dot indicates two sensors placed next to each other but not connected to each other. One of the sensors at this location connects in series to other sensors located in a horizontal row. This type of connection is termed a continuous sensor [1]. The continuous sensor with the analog processor is called a neuron. The output of the neuron is the combination of the signals from all the sensor nodes forming the neuron. The advantage of

the neuron is that it can detect transient signals due to damage occurring at any of the nodes, and the neuron produces only one time signal. In Figure 1(a) there are ten row neurons. Similarly, there are ten column neurons. In all, twenty channels of data acquisition would be required to individually monitor the neurons. A further reduction in the number of channels of data acquisition is achieved by combining the outputs of the neurons and keeping tract of which neurons are firing. The output of the first ten channels (column neurons v1 to v10) is input to the SNS analog processor (SNSAP 1) which reduces the required number of data acquisition channels to only two using firing of the neurons. One of the channels (C1) predicts the location of damage based on firing of the neurons. An algorithm is used to decode the firing signals and tell which neurons are firing. The other channel (T1) is the actual time response of the neuron and qualitatively predicts the severity of the damage. The same procedure follows for the row neurons (V11 to V20) using the SNSAP 2 processor and the outputs C2 and T2. Thus, with an arbitrary number of sensor nodes, only four channels of data acquisition are required to predict the location and estimate the severity of the damage.

The advantage of the SNS is that the system is mostly analog and this eliminates the many channels of data acquisition or multiplexers with high sampling rates that are conventionally required. Also, the SNS system is user friendly and damage is easily located by the order of firing of the neurons. The same SNS can be used for both passive and active health monitoring. Passive monitoring involves the detection of stress waves produced due to the progression of damage. Active monitoring involves excitation of the structure using an actuator and comparing the baseline firing signal and the firing signal when the structure is damaged. Up to ten or more neurons can be connected together in rows and in columns using firing and decoding.

To design the SNS, it was important to model wave propagation in the material. Thus, a closed form solution of wave propagation in a panel was developed based on classical thin plate theory and modal superposition. Wave speeds were compared between the modal superposition method, classical thin plate theory, and the Lamb wave solution. There was good agreement between the modal superposition method and classical thin plate theory. Since classical thin plate theory neglects transverse shear and rotary inertia [2], the higher order Lamb wave theory is more accurate for thicker plates and higher frequencies. The wave simulation algorithm is found to be a useful tool for designing and optimization of SNS.

A prototype SNS was developed and tested with four sensor inputs. The test plate is shown in Figures 1(b) and 1(c). Two types of SNS were tested, namely passive and active SNS. For passive SNS, sensors one through four as identified in Figure 1(b) is used for damage detection.

For passive SNS a pencil lead break simulating an acoustic emission is provided on the surface of the composite at the location indicated by “X” in Figure 1(b). The output of sensors is passed into SNS analog processor for efficient signal processing and damage detection. Figure 2(a) shows the final output generated by the SNS. The SNS indicates that the damage is located near sensor 1 which is true as the acoustic emission was placed near sensor 1 as shown in Figure 1(b).

Testing of the active SNS was also performed. In active SNS the baseline signal is compared with the damaged signal and any difference in the signal accounts for an existing damage. Figure 1(c) shows a reinforced aluminum plate bonded near sensor three. The damage was simulated by removal of the bonded aluminum plate. The baseline and the damage signals were recorded and the SNS indicated that the damage was located near sensor 3, as shown in Figure 2(b). Note that for both active and passive SNS only one digital channel (Figures 2(a) and 2(b)) is used for damage location. Overall, the SNS is a simple practical approach for SHM and different types of sensors can be used including piezoelectric ceramics and carbon nanotubes to detect damage and corrosion.

6177-18, Session 3

Development of 3D vibration measurement system using laser doppler vibrometers

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Collapse of civil infrastructures can occur because of aging or damage deterioration. Thus, there is a need of an effective structural health monitoring (SHM) technique to ascertain the safety of these structures. Laser Doppler Vibrometer (LDV) is one of the effective measurement devices to use for SHM. It can be used for non-contact and long distance measurement. In addition, multiple point measurement is also possible by using a scanning unit.

In the previous studies, the LDV can only be used for one-dimensional (out-of-plane) measurement. Since, the in-plane vibration components are also important in many applications, there is a need to develop a three-dimensional measurement system. The objective of this study is therefore to develop a high precision three-dimensional measurement system using LDVs. In this paper, a three-dimensional measurement technique using three LDVs for single point measurement is proposed. The principle of the system, the investigation of the laser beam angles and the measurement distance are presented.

The principle of the three-dimensional measurement is a geometrical transformation of coordinates. The vibration components of a body are measured by three LDVs at different angles and then they are transformed into three-dimensional vibration components by using a transformation matrix derived from the angles of the laser beams.

In this technique, first, the laser beam angles must be determined. To determine these angles, spatial movement information of laser spots is used. Three laser spots are converged on a calibration board. When the board is moved, laser spots are moved on the board spatially. Then, by measuring the movement distance of each spots, laser beam angles are calculated and a geometrical transformation matrix is constructed. Finally, three-dimensional vibration components of a body are calculated from the measurements by three LDVs by using the transformation matrix.

The proposed system is tested by measuring a movement of a tri-axial accelerometer. The accelerometer is hung and blown by a fan. The measurement results agree well with the results obtained from the accelerometer. It is also investigated that the system has a flexibility to be set at different angles and can measure up to a distance of 3 m. Finally, the proposed system is applied to measure ground motion and wave propagation in plates.

6177-19, Session 4

Concrete damage evaluation by active acoustic modulation

H. Wu, Wayne State Univ.

Non-destructive testing for constructed facilities has been attracting researcher’s attention in recent decades because that our infrastructure system is deteriorating at an alarming rate. Acoustics is considered to be one of the most promising methods. Non-linear nondestructive testing is different from linear acoustic in that it correlates the presence and characteristics of a defect with acoustical signals whose frequencies differ from the frequencies of the emitted probe signal. The difference in frequencies between the probe signal and the resulting frequencies is due to a nonlinear transformation of the probe signal as it passes through a defect. Under acoustic interrogation due to longitudinal waves, as the compression phase passes the defect the two sides of the interface are in direct contact and the contact area increases. Similarly, the tensile phase passes through the defect, the two sides separate and the contact area decreases, thereby modulating the signal amplitude. In this paper, such effect will be discussed and preliminary experimental data on evaluation of concrete damage will be presented.

6177-20, Session 4

Integrity testing for drilled shafts by crosshole sonic logging and gamma density logging: a comparative study through observations and interpretations

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Development of Non Destructive Testing (NDT) methods has greatly increased in recent years. Principle objective of this development is to provide reliable assessment of the structures by employing appropriate test method and proper interpretation of data collected in the field. Nowadays NDT of deep concrete foundation is gaining popularity enormously. In order to ensure structural stability and structural integrity, obtaining accurate and timely information about construction defects is inevitable for deep foundations. Crosshole Sonic Logging (CSL) has become very popular as an useful method for shaft integrity testing. Nowadays shaft integrity testing by GDL is much easier than earlier because of profound advancement of this method. CSL is comparatively new method than GDL. CSL employs ultrasonic wave velocity to investigate defects in shafts whereas, GDL employs nuclear source to predict material density around the probe. Both methods have advantages and disadvantages. Through investigation it has been found that only one method is not sufficient to ensure the integrity of the shafts. Sometimes, the anomalies detected by the CSL method are underestimated or overestimated. Proper understanding of zone of influence of these two methods is inevitable for more accurate evaluation of the shafts. Different types of anomalies can occur, some of them are severe and some of them are really insignificant. Understanding of degree of measured judgment by both methods is expected and need to be classified. Severe defects like concrete contamination, large size voids, concrete mixed with slurry, soil intrusion inside the shafts can be measured efficiently by CSL. But several incidences happen where one can receive total signal loss. In such situations two decisions can be made either the shaft contains severe defects or the Poly Vinyl Chloride (PVC) pipes are debonded from the concrete. CSL employs ultrasonic wave to determine the First Arrival Time (FAT) of the wave at the re-

ceiver transducer. Water in the PVC tubes is used as a couplant fluid. In this condition the debonding between concrete and PVC resists the signal to propagate in the concrete and causes total loss of signal. GDL can be a very good confirming method in this situation. A correlation between material density reduction from GDL and velocity reduction from CSL are studied and presented in this work for better understanding of the issues and for better characterizing the anomalies in the shafts. Several practical cases are studied to understand and present the correlation, zone of influence and capabilities of these two NDT methods. Sometimes, degree of concern due to defects found from GDL can be much severe than degree of concern found from CSL. It is not expected to have the same degree of concern found from both methods. Implicit understanding of zone of influence is very efficient in solving doubts on severity of defects. Hence, dual method is recommended to inspect the integrity of the shafts depending on the importance of the structures. This work presents the proper characterization of the defects in the shafts using correlation between GDL and CSL data from various practical projects.

6177-21, Session 4

Study on structural evaluation of pavement using surface wave and portable FWD tests

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Research on SASW (Spectral analysis of surface wave) has been well known as one of nondestructive testing methods for pavements. This method makes use of the dispersion characteristics to estimate pavement structure. It is difficult to obtain accurate dispersion curves even if the analytical surface wave fields are used, where only the stiffness damping is considered. However, the good agreement of dispersion curves has been found for the analytical surface wave fields if Rayleigh damping is adopted in the numerical simulation. In this paper, a general FEM software was developed to inverse the layer moduli and Rayleigh damping of testing pavement using the portable FWD data. It shows that the predicted dispersion curves are well approximately to the measured ones.

6177-22, Session 5

Ultrasonic imaging of hidden corrosion and cracks using dry-coupled ultrasonic probes

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Safety criteria of aircraft industry require careful inspection of aircraft components for structural integrity since airworthiness of aging aircraft can be significantly affected by combination of corrosion and fatigue damage.

Surface corrosion and cracks can be efficiently detected by visual or other surface inspection techniques. Detection of hidden corrosion and cracks, on the other hand, is still a challenging task. Therefore, it is essential to develop non-destructive methods that can inspect different layers of the aircraft structures for corrosion and cracks before they become a safety concern.

Ultrasonic inspection is one of the most widely used methods in aerospace industry. This method can provide comprehensive information on internal defects in the various formats. However, ultrasonic techniques require different forms of water or gel couplants as transmission interfaces between the inspected materials and ultrasonic probes. In many cases two-dimensional scanning of large aircraft panels in immersion mode is simply not feasible, so adequate coupling may only be achieved by the application of expensive scanning systems with water jets or gel couplants. Application and removal of the gel couplants is also a time-consuming procedure, especially if a large panel is to be tested. Some advanced aircraft structures entirely prohibit the application of wet-coupled inspection techniques to prevent contamination or degradation of the materials or coatings that are sensitive to the couplants.

One of the possible ways to eliminate the need for liquid or gel couplants is deployment of flexible polymer coupling substrates. This flexible substrate easily deflects and conforms around irregularities of the inspection surfaces when in contact with the test piece. Dry-coupled substrates can be applied on the components with curved or rough surfaces without paint removal or surface cleaning that will substantially decrease inspection time for large area aircraft components.

Ultrasonic probes with the dry-coupled substrates are highly efficient for all modalities of ultrasonic techniques including pulse-echo, pitch-catch, or through-transmission modes. The probes can be deployed in conjunction with portable ultrasonic instruments for B- and C-scanning. The dry-coupled probes have already been tested on a number of aircraft for rapid inspections of the aircraft structures from the outside without any disassembly.

However, adequate inspection for small pitting corrosion and incipient fatigue cracks may require superior sensitivity and resolution of the applied ultrasonic technique. Several novel designs and configurations of the dry-coupled probes with increased sensitivity and resolution will be presented. Ultrasonic imaging with single- or double-element dry-coupled probes will be demonstrated on the panels with heavy pitting corrosion and machined planar and volumetric defects.

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6177-23, Session 5

Characterization of damaged pipelines utilizing ultrasonic measurements

P. D. Panetta, Pacific Northwest National Lab.

Maintaining the integrity of the nation's aging infrastructure is of primary importance. Specifically there is a desire to characterize degradation to the civil infrastructure to monitor its integrity. Of particular importance is the accurate prediction of the lifetime of damaged natural gas pipelines due to outside force. In order to accurately predict the remaining life it is essential to accurately determine the degree stress and strain in damaged regions for input into fracture mechanics models. Currently, determination of the degree of stress and strain in damaged regions utilizing ultrasonic velocity measurements is complicated by the inherent texture variations in the alloys and the difficulty in separating these effects from the stress and strain contributions. We will report ultrasonic measurements on plastically deformed steel specimens and natural gas pipelines to elucidate the state of damage in dented and bent regions. Specifically, we have found the shear wave birefringence is directly related to the degree of plastic strain and residual stress. Ultrasonic results will be compared with finite element modeling calculations of the stress and strain distributions and analytic theories of the effects of stress and strain on the ultrasonic measurements.

6177-25, Session 5

Ultrasound detection of damage in complex carbon fiber/metal structures

G. J. Thursby, A. MacLean, H. Hogg, B. Culshaw, Univ. of Strathclyde (United Kingdom)

We describe work carried out to monitor the structural health of a complex structure comprising both carbon fibre and metal components using ultrasound techniques. The work is designed to be used in a high performance car, but could find applications in other areas such as the aerospace industry. There are two different types of potential problem that need to be examined; the first is damage (e.g. holes, delaminations) to carbon fibre structure, and the second is damage to joints either between two carbon fibre components or between a carbon fibre component and a metallic one. The techniques used are based around the use of PZT transducers for both the generation and detection of ultrasonic Lamb waves. To date we have been carrying out experiments on mock-up samples, but are due to conduct tests on an actual vehicle.

Lamb waves propagate in modes whose order is determined by the frequency thickness product. Their properties, such as phase and amplitude can be modified by the presence of damage, such as holes and delaminations. If we record the response of a healthy structure, we can then compare it with signals obtained on subsequent occasions to determine if any significant change has taken place. It is essential, however, to be able to differentiate between the effects of damage and those of environmental changes such as temperature. For this reason we have monitored the response of a sample at different temperatures both before and after drilling a hole in it to simulate damage. Depending on the positions of the transducers with respect to the damaged area, it is possible to detect either attenuation of the entire signal or changes in a specific portion of the signal produced by reflections. Results from these experiments will be presented at the conference. Signal processing techniques for separating damage from the effects of temperature will also be discussed

We also look at the deterioration of joints, which can either be epoxy bonded (carbon fibre to carbon fibre) or bolted together (carbon fibre to aluminium). In the case of the bonded structures we are looking at the effects of failure of the bond layer, whilst in the case of the bolted samples we are looking at loosening of the bolts. The debonding was simulated by joining together a flat plate of carbon fibre composite with an L-shaped carbon fibre piece using a couplant such as grease. Similar experiments were carried out using an aluminium anglebar bolted to the plate, with the bolts both tightened and loose. Signals of both the transmitted wave in the plate and the power coupled to the L piece were measured before and

after debonding. This gives a more reliable measure of the change in power transfer between the two components as the joint/bond degrades. It was found that in order to get maximum coupling to the second component the frequency of the acoustic wave had to be altered. This is because in the bonding region the combined thickness of the components alters the modal propagation characteristics of the structure compared with those of the single component region.

6177-26, Session 5

Hilbert-Huang decomposition of time signals for structural damage detection

P. F. Pai, L. Huang, Univ. of Missouri/Columbia

In the last few decades structural engineers and researchers have been developing dynamics-based methods for rapid damage inspection of large structures. Damage detection is challenging because it is an inverse engineering problem. Based on the complexity of sensor systems, signal processing methods, and accuracy of deduced damage indicators, dynamics-based damage detection methods can be separated into three groups. Methods in the first group require a simultaneous full-field measurement tool, and they process the measured distributed displacement, slope, or velocity field (e.g., using Moire interferometry, digital shearography, or scanning laser vibrometers) to obtain strains and/or curvatures and then locate damage by examining abnormality or sudden change of these spatially distributed data. Methods in the second group require simultaneous measurements of many points, and they use a well calibrated model of the original intact structure and a modal expansion/update technique to locate damage. Methods in the third group require simultaneous measurements of only a few locations, and they use the measured time traces and the traveling sequence of abnormality or sudden change in the time traces to locate damage. In-work dynamics-based damage detection methods usually use the third approach. Methods in the first group process spatially distributed data to extract physical variables (such as slopes, curvatures, and strains) to directly reveal damage locations, but the challenge is how to extract clear damage indicators from the large amount of data obtained from a full-field measurement. Methods in the second group use the calibrated structural model and measured data to compute spatially distributed physical variables to estimate damage locations, but the challenge is how to repeat the same setup conditions originally used for the structural model and how to correlate the model with currently measured dynamic responses that may be affected by unknown damage and/or changes of physical conditions (such as surrounding temperature change, moisture absorption, and minor changes of boundary conditions). On the other hand, methods in the third group process time-domain data to extract time-varying dynamic characteristics (i.e., vibration frequencies, damping ratios, and nonlinear phenomena) to reveal the existence of damage, but the challenge is how to extract linear and nonlinear dynamic characteristics from dynamic responses (especially transient responses) and how to correlate the time-varying dynamic characteristics obtained at just a few physical locations to damage locations.

This paper presents a new third-group method that processes transient and/or steady-state time signals measured at just a few physical points on a structure to extract time-varying linear/nonlinear dynamic characteristics and then uses the variation and propagation of dynamic characteristics to reveal damage and estimate damage locations. A linear structure has constant natural frequencies, and it vibrates at the frequency of an externally applied harmonic excitation. On the other hand, a nonlinear structure has amplitude-dependent natural frequencies, and it may vibrate at a frequency different from an externally applied harmonic excitation. Moreover, even under small vibrations dynamic responses of a damaged structure can be nonlinear because of damage, such as the opening and closing of cracks. Other nonlinear phenomena include multiple-harmonic response under a single-frequency harmonic excitation, intrawave amplitude- and phase-modulated motions, and multiple-mode vibrations caused by modal interaction (i.e., interwave modulation). For extracting time-varying linear/nonlinear dynamic characteristics from transient and/or steady-state dynamic responses we use the Hilbert-Huang transform (HHT) and a sliding-window fitting (SWF) technique. Numerical results show that major nonlinear phenomena that can be extracted include different nonlinearities, softening and hardening effects, intrawave amplitude- and phase-modulation, distorted harmonic responses under a single-frequency harmonic excitation, interwave amplitude- and phase-modulation, and multiple-mode vibrations caused by internal/external resonances. However, the discontinuity-induced Gibbs' phenomenon makes HHT analysis inaccurate around the two data ends. On the other hand, the SWF analysis has no Gibbs' phenomenon at the two data ends, but it cannot extract accurate modulation frequencies due to the use of non-orthogonal basic functions in the sliding-window least-squares curve fitting process. The existence and propagation of extracted time-varying dynamic characteristics are used to reveal and locate damage locations. Numerical and experimental results obtained using a Polytec PI PSV-200 scanning laser vibrometer to measure vibrations of several structures (including one cracked beam and one 30"x22.8"x0.2" aluminum plate) validate the efficiency and accuracy of this newly developed technique.

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6177-27, Session 6

Tailored excitations for structural health monitoring via evolutionary programming

C. C. Olson, M. D. Todd, Univ. of California/San Diego

Dynamic interrogation of structures for the purposes of damage identification is an active area of research within the field of structural health monitoring (SHM) with recent work focusing on the use of chaotic excitations and state-space analyses for improved damage detection. Inherent in this overall approach is the specific interaction between the chaotic input and the structure's eigenstate. The sensitivity to damage is enhanced by special tailoring of the input in terms of stability interaction with the structure. This work outlines the use of an evolutionary program to search the space of possible excitations, subject to a constraint hierarchy, for those excitations that are best suited to appropriately interact with the structure for enhanced damage detection. State-space damage identification metrics are used to detect damage in a computational model driven by excitations produced via the evolutionary program. Non-optimized excitations such as white noise and the chaotic Lorenz oscillator are used as comparison cases.

6177-28, Session 6

Wireless intelligent sensor and actuator network (WISAN): a scalable ultra-low-power platform for wireless structural health monitoring

E. S. Sazonov, R. Jha, K. D. Janoyan, V. Krishnamurthy, M. Fuchs, K. Cross, Clarkson Univ.

This paper presents Wireless Intelligent Sensor and Actuator Network as a scalable wireless platform for structural health monitoring. Design of WISAN targeted key issues arising in applications of structural health monitoring. First, scalability of system from a few sensors to hundreds of sensors is provided through hierarchical cluster-tree network architecture. Special consideration is given to reliable delivery of wireless data in real-world conditions. Second, a possibility of autonomous operation of sensor nodes from energy harvesters is ensured through extremely low power consumption in operational and standby modes of operation. Third, all the sensors and actuators operate in globally synchronized time on the order of a few microseconds through utilization of the beaconing mechanism of IEEE802.15.4 standard. Fourth, depending on application requirements, the system is capable of delivering real-time streams of sensor data or performing on-sensor storage and/or processing with result transmission. Finally, a capability to work with heterogeneous arrays of sensors and actuators is ensured by a variety of analog and digital interfaces.

Results of experimental tests validate the performance of the WISAN.

6177-29, Session 6

A miniaturized electromechanical impedance-based sensor node for the wireless interrogation of structural health

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This paper presents the development and applications of a miniaturized impedance sensor node for structural health monitoring. The principle behind the impedance-based structural health monitoring technique is to apply high frequency structural excitations (typically higher than 30 kHz) through the surface-bonded piezoelectric transducers, and measure the impedance of structures by monitoring the current and voltage applied to the piezoelectric transducers. Changes in impedance indicate changes in the structure, which in turn can indicate that damage has occurred. Although many proof-of-concept experiments have been performed using the impedance methods, the impedance-measuring device is bulky and impractical for field-use. Therefore, we used a recently developed, low-cost impedance measurement chip that can measure and record the electric impedance of a piezoelectric transducer. The performance of this miniaturized and portable device has been compared to our previous results and its effectiveness has been demonstrated in detecting bolt preload changes in a bolted frame structure. Furthermore, the possibility of wireless communication and local signal processing at the sensor node has been investigated by integrating the device with a microprocessor and radio frequency identification (RFID) technology.

6177-30, Session 6

Fracture and self-healing of multilayered membranes

W. Ngwa, W. Luo, Univ. of Central Florida

In studies of solid supported solid-like and liquid-like lipid bilayers with the AFM, fracture has been observed and discussed in several studies. Here we examine mechanical failure (fracture or break-through) where the influence of the supporting substrate is eliminated, i.e. for sufficiently thick films. Using such thick films also allows for the effect of substrate coupling to be monitored by examining any changes in Young's modulus for different thicknesses. Fracture curves, where the cantilever contacted the substrate, could be used directly to determine the local film thickness. For DOPC, we observed fracture with different characteristics including multiple jumps, and single breakthrough events. The elastic regions of the force curves were used to determine local Young's moduli by the Hertz model. Results for force curves that exhibit reproducible and non-reproducible fracture are presented and discussed with respect to self-healing of the membranes.

6177-31, Session 6

Using attractor localization to improve nonlinear prediction error for structural health monitoring

L. A. Overbey, M. D. Todd, Univ. of California/San Diego

Recently, damage sensitive features extracted from the phase space reconstruction of a structural response have proven to be successful for use in the field of structural health monitoring. One such feature utilizes the evolutions of randomly selected points on a baseline attractor to predict evolutions of corresponding points on an attractor in some unknown state of health. The error based on this prediction can be employed to determine the presence and/or extent of damage. One drawback of this approach is that some regions of the attractor geometry may be more or less sensitive to damage-induced changes in the dynamics. Thus, prediction error could incur large variances in its distribution, and results could change significantly depending on the size and location of the randomly selected subset of points used for prediction. This paper examines the effect of spatial location on prediction error in an effort to better utilize the geometry of phase space. Investigations will be conducted on a filtered chaotic excitation and an experimental test structure.

6177-26, Session 7

A new replication method to fabricate polymer waveguide

W. Chuang, C. Ho, R. F. Shyu, F. T. Weng, National Formosa Univ. (Taiwan); W. Wang, Univ. of Washington

Polymer waveguides were successfully fabricated using a new replication process, which was simple and easy process. The SU-8 polymer was used as a negative photo register and core layer of the waveguide, and the deep and vertical channel of the waveguide could be achieved by this process. In this experiment, the waveguide was patterned on the SU-8 polymer by the NUV light lithography, and the PDMS polymer was used as a stamp to transfer the waveguide structure pattern into the PDMS mold. The near-field measurement with end-fire coupling was used to measure the optical intensity of polymer waveguides that reproduced by the PDMS mold, and it has shown that the light had been totally restricted inside the core layer of the waveguide.

6177-32, Session 7

Composite optical bend loss sensor for pressure and shear sensing

W. Wang, C. Huang, Univ. of Washington

Lower limb complications associated with diabetes include the development of plantar ulcers that can lead to infection and subsequent amputation. While it is known from force plate analyses that there are medial/lateral and anterior/posterior shear components of ground reaction forces, there is little known about the actual distribution of these stresses during daily activities, nor about the role that shear stresses play in causing plantar ulceration. Furthermore, one critical reason why these data have not been obtained previously is the lack of a validated, widely used, commercially available shear sensor, in part because of the various technical issues associated with shear measurement. In this study, a novel means of transducing plantar shear and pressure stress via a new composite optical bend loss sensor is presented. The fabrication process of the composite optical bend loss sensor involves an injection molding technique with optical fibers embed into the Polydimethylsiloxane (PDMS). The pressure/shear sensor consists of an array of optical fibers lying in perpendicular rows and columns separated by elastomeric pads. A map of normal and shear stress is constructed based on observed macro bending through the intensity attenuation from the physical deformation of two adjacent perpendicular fibers.

6177-33, Session 7

Ultrasonic correlation procedures for signals observed with amplitude and phase contrast

Z. Kojro, M. von Buttlar, E. Twerdowski, W. Grill, Univ. Leipzig (Germany)

Electronic processing and numeric evaluation has been developed and employed for acoustic correlation measurements. Special electronic schemes have been developed to allow for correlation of signals based on vector contrast (phase and amplitude;quadrature) detection schemes. Numerical processing has also been adapted to the complex detection scheme. The developed instruments and methods have been employed for correlation measurements and analysis of the data obtained for micrometer sized (2 to 10 μm) particles (polystyrene) in water. The results are compared to results obtained with established optical correlation detection and evaluation schemes. The methods have been developed to study the behavior of miniature aquatic animals (daphnia).

6177-34, Session 7

Measurement of thin film interfacial properties using nanosecond laser source

A. K. Mal, Univ. of California/Los Angeles; S. Banerjee, St. Louis Univ.; V. Gupta, Univ. of California/Los Angeles

A high energy Nd:YAG laser source is used to determine the intrinsic adhesion strength of thin films deposited on substrates. The specimen is designed to convert the thermal energy of the short duration laser pulse to a strong compressive stress on the back face of the substrate. The compressive stress propagates through the layered structure, and upon reflection from the free surface of the film, generates a tensile wave which produces tensile failure of the interface. The stress associated with the interface failure is calculated from a theoretical model of wave propagation through the layered medium. The compressive stress produced by the laser source is determined from a second experiment involving the homogeneous substrate by removing the film. Examples of the applications of the technique in microelectronics and cell biology are presented.

6177-35, Session 7

Voltage injection and readout method for PCB (printed circuit board) testing

G. Zentai, Varian Medical Systems, Inc.

An electrostatic imager for PCB testing was proposed by Varian in a previous paper (G. Zentai, L. Partain, C. Proano, S. Yamaoka "A New Unique Electrostatic Imager for Non-Destructive Evaluation of Printed Circuit Boards", Proc. of SPIE - NDE 2001, Vol: 5047 p:67, and also US patent "Electrostatic imager", patent # 6,921,892). The described method used a pulse generator connected to a pin addressing array, which pins were in direct contact with the traces of the PCB to be tested. The PCB was laid on to a pixelated readout matrix but it was separated from the readout pixels by an insulator foil. The readout matrix retrieved the charges induced in the pixels under the trace to detect and image the shape and size of the trace addressed by the voltage pulse of the pin addressing array. In the case of short circuit, not only the image of the addressed trace is visible but also a second trace shorted to the addressed one; if there is an open circuit, only part of the trace is visible.

The previous method works fine but has some drawbacks. It needs a complicated pin matrix array to address each trace separately. The switching of the address pulse from pin to pin is difficult in case of a large area array to be tested with lots of traces. Finally, the signals read out from the pixels are relatively small in comparison to the voltage applied to the traces because of the capacitive coupling.

A new idea has been developed for applying voltages on to the traces with an addressing matrix different from the pin addressing one. This matrix is similar to the readout matrix that the above patent referenced to but instead of readout circuits, driver circuits are connected to the pixels to apply voltages on to them. The printed circuit board is laid on top of the array but rather than using an insulator foil, directional conducting foam or rubber layer is applied between the excitation matrix (array) and the PCB. We get direct coupling of the pixels to the PCB (traces) and no connection between neighboring pixels (traces) using the directional conductive layer which conducts only in z direction and not in x (and y) direction. Therefore, by addressing each pixels separate, which is easy to do by software, we get an addressable voltage (pulse) injector matrix.

The same directional conducting foam coupling can also be used for reading out

the image of traces. Because the capacitive coupling is eliminated, the detected signal increases and so the sensitivity.

6177-37, Session 7

Mathematical model for the dynamics of a optical fiber viscometer

W. Wang, J. N. Ho, Univ. of Washington

This paper presents a mathematical model for the dynamics of a optical fiber viscometer by using a partial differential equation (PDE) based on a one dimensional, damped wave equation. This model contains the affects from the discontinuty caused by partial immersion of a vibrating fiber in liquid by applying a Heavside step function over the immersed part of the fiber. The subsequent solution of the mathematical model gives results that accurately follows the trends of experimental results.

6177-38, Session 7

Combinatory scanning confocal laser and acoustic vector contrast microscopy

A. Kamanyi, Jr., R. Wannemacher, W. Grill, Univ. Leipzig (Germany)

Synchronous operation of confocal laser scanning microscopy and confocal vector contrast scanning acoustic microscopy (phase sensitive scanning acoustic microscopy: PSAM) has been developed. Imaging is performed on objects mounted on a cover slide with the CLSM operated in reflection through the slide and PSAM operating in water or aqueous solution from the other half space. Examples involving living cells and soft matter samples illustrating various combinatory schemes and advantages of multi-contrast optical (electromagnetic) and acoustic (mechanical) contrast are demonstrated. These include combinations with fluorescence microscopy and ultrasonic topographical imaging as well as combinatory three-dimensional imaging.

6177-39, Session 7

Ultrasonic wireless health monitoring

L. Petit, E. Lefeuvre, D. Guyomar, C. L. Richard, P. Guy, K. Yuse, T. Monnier, Institut National des Sciences Appliquées de Lyon (France)

Over the years there has been a growing interest in miniature sensors in many field of applications such as embedded sensors in vehicles, health monitoring, non destructive control, etc...

The proliferation of transducers and sensors raises the problem of wires installation for power supplies and data transmission. A wireless system, based on vibration energy harvesting, will increase the system reliability.

If the use of primary batteries is a classic solution for the power supply, they unfortunately have a finite amount of energy, a limited capacity retention and a short shelf life (few years).

Fortunately, the continuous decrease of the electrical power requirement for electronic circuits allows now the use of autonomous micro-power piezoelectric generators exploiting the structural vibrations.

Our goal is to implement such an energy harvesting system for powering a single AWT (Autonomous Wireless Transmitter) using our SSH (Synchronized Switch Harvesting) method. Based on a non linear process of the piezo-patch voltage, this SSH method optimizes the energy extraction from the mechanical vibrations. It appears that for a given vibration amplitude, the harvested energy can be increased by nearly a factor 10 using the SSH approach compared to the standard piezoelectric methods (piezoelectric elements connected with a rectifier and a filter capacitor to provide a DC voltage to the load). It is also shown that our technique is especially efficient for low coupling structure.

The AWT is integrated in a health monitoring network where several self-powered transmitters communicating with a powered central receiver.

This self powered system has two main functions : The generation of an identifier code by RF transmission to the central receiver and the Lamb wave generation for the health monitoring of the host structure. A damage index can be derived from the variation between the transmitted wave spectrum and a reference spectrum. The same piezo-patches are used for the energy harvesting function and the Lamb wave generation, thus reducing mass and cost. A micro-controller drives the energy balance and synchronizes the actions : At each time the harvested energy in the storage capacitor reaches the requested threshold, a RF transmitter emits an identifier code to the central receptor. A pulse voltage is then applied on the piezo-elements and generates a Lamb wave emission. Such an autonomous transmitter has been evaluated on a 300x50x2 mm3 composite cantilever beam. Four 33x11x0.3 mm3 piezo-elements are used for the energy harvesting and for the wave lamb generation. A piezoelectric sensor is placed at the free end of the beam to track the transmitted Lamb wave.

In this configuration, the needed energy for the RF emission is 0.5 mJ for a 1 byte-information and the Lamb wave emission requires less than 0.1mJ. An energy quantity of approximately 6 mJ is harvested with a 470 μF storage capacitor. Theoretical and experimental results will be given.

6177-48, Poster Session

Anemia detection utilizing diffuse reflectance spectra from the palpebral conjunctiva and tunable liquid crystal filter technology

J. W. McMurdy III, Brown Univ.; G. D. Jay, S. Suner, Rhode Island Hospital; G. P. Crawford, Brown Univ.

The dominant method of anemia detection is an invasive complete blood count test, however this remains an antiquated technique in the contemporary climate of noninvasive diagnostics. Anemia, or a shortage of oxygen transporting hemoglobin (<13 g/dL for male, <12 g/dL for female), is clearly manifested at the inner mucosal lining of the eyelid, the palpebral conjunctiva. The hue of the palpebral conjunctiva depends on the hemoglobin concentration with healthy levels being a bright red, and lower levels being a paler tint. The palpebral conjunctiva is an attractive location to monitor total hemoglobin concentration because of the blood vessels proximity to the surface, the conjunctival membranes transparency, and the accessibility of the inner eyelid. Other studies on noninvasive hemoglobin measurement have been limited to the evaluation of transmission/reflectance visible/NIR signals from cutaneous tissues rather than mucosal surfaces, and thus have been hindered by high scattering, melanin absorption (in the visible regime), and absorptions from other species such as water (in the IR regime) A physicians qualitative observation of the conjunctival hue has been shown to be at best 70% accurate in diagnosing clinical anemia as it is subject to color interpretation. A spectroscopic evaluation of the conjunctiva using grating spectroscopy has been proven here in a clinical trial to enhance predictive accuracy as well as anemia detection specificity and sensitivity while remaining a noninvasive technique. The conjunctiva is white light illuminated (examined from 380-780nm) at a safe irradiance level, and diffuse reflectance signal is collected and analyzed using multivariate regression techniques. The average error of prediction using conjunctival diffuse reflectance spectroscopy was found to be 0.55 g/dL with a Pearson correlation coefficient of 0.95, both enhancements over studies analyzing cutaneous tissues. Additionally, this accuracy was comparable across ethnicities, likely due to low inter-patient melanin variations at the mucosal surface of the conjunctiva. While this accomplishment is noteworthy, integrating a grating-based spectrometer into a bedside device is not an optimal solution due to cost, size, and durability. Spectrally switchable and tunable filters based on liquid crystals (LC) may be used to mimic spectrometer performance and fabricate an inexpensive sensor device which measures total hemoglobin at the bedside. Integrating a white light filament and photodiode/CCD photodetector with LC filter stacks affords portability for rapid anemia screening, a useful facets in applications such as emergency medicine. Three approaches can be made to the liquid crystal filter solution including switchable holographically formed polymer dispersed liquid crystals (HPDLC's), tunable cholesteric liquid crystals (CLC's), and deformed helix ferroelectric liquid crystals (DHFLC's), each with differing spectral and electro-optical properties. The efficacy of each technology as a component of this device is assessed here including reflective efficiency, bandwidth, and switching/tuning speeds. The ability of each embodiment to resolve spectral features is assessed and compared to that of a grating spectrometer using a standard Hg lamp source. Acquisition times were monitored by recording elapsed time for each filter type to recreate spectral features.

6177-40, Session 8

Locating and quantifying impact forces on a compliant torso using acceleration mapping

A. A. Cardi, D. E. Adams, Purdue Univ.

This research experimentally implements a new method to identify the location and magnitude of a single impulsive excitation to ceramic body armor, which is supported on a compliant torso. The method could easily be extended to other flexibly supported components that undergo rigid body dynamics. Impact loads are identified in two steps. First, the location of the impact force is determined from time domain acceleration responses by comparing them to an array of reference acceleration time histories. Then based on the estimated location, reference frequency response functions are used to reconstruct the input force in the frequency domain through a least squares inverse problem. Experimental results

demonstrate the validity of this method at both low energy excitations, which are produced by a medium modally-tuned impact hammer, and at high energy excitations, which are produced by dropping rods with masses up to 0.6 kilograms from a height of 2 meters. The maximum error in the estimated location or magnitude for the low energy excitations on the 10 cm square ceramic body armor was 7.07 mm with an average error of 1.09 mm. In comparing the estimated force for the low energy excitations to the force recorded by the transducer in the modal impact hammer, the maximum error in the predicted force amplitude was 6.78 percent and the maximum error in the predicted impulse was 6.44 percent. For the high energy excitations, which produced accelerations at the measurement locations up to 50 times greater than that of the low energy excitations, the maximum error in the predicted location of the input force was 15 mm with an average error of 6.64 mm. There was no force transducer to capture the input force on the body armor from the rod, but from non-energy-dissipative projectile motion equations the validity of the solutions was confirmed by comparing the impulses. The frequency response functions (FRFs) used to reconstruct the force input from the rods had a range of 49.152 kHz, which was higher than the Nyquist frequency for the FRFs used to calculate the input force of the low energy excitations. This low frequency range was poorly excited by the metal-tipped modal impact hammer used to generate the FRFs, which only excited out to 10 kHz; the point where the input power spectrum decreased by -20 dB. Despite this limitation, responses from impact points near the center of the tile were successfully used to reconstruct the input forces with impulses close to theoretical predictions. This result was due to the fact that higher frequency content was introduced into the measurement signals the further away the impact was from the body armor's center of mass.

6177-41, Session 8

The development of piezoelectric oscillator sensor for in vivo monitoring of capsule formation around soft-tissue implants

B. Xu, V. Giurgiutiu, G. S. Crachiolo, Univ. of South Carolina

The cellular response to the placement of a foreign substance, particularly silicone, into the soft tissues has been fairly well characterized histologically. While some studies exist that have measured capsule mechanical properties, they are currently limited to static measurements of elasticity, compliance, and capsular pressure. Monitoring biochemical concentrations in vivo using implanted devices has been the subject of intense research efforts. Some researchers have explored the utilization of QCM to monitor capsule formation around soft tissue implants. However, this type of sensor is relatively large in size and too brittle to survive the vivo experiments.

In our study, we set forth to perform such dynamical measurements using piezoelectric wafer active sensors (PWAS, 7mm diameter disc) oscillator circuit. The PWAS, which are widely used in structural health monitoring, will be modified for biomedical application. The oscillator resonates at the first resonant frequencies of PWAS in radial mode and tracks how these value changes with various physical parameters. Firstly, we present the design of this PWAS oscillator with SPICE simulation. The oscillator is based on Colpitts oscillation circuit. At the resonant frequencies, the PWAS work as inductances. Secondly, to validate the circuit, the oscillator will be tested in vitro in various types of gels which simulate the contraction of capsules. Finally, the PWAS will be implanted into rats to analyze the response of the surrounding soft tissues to these devices. The recordings from these sensors will be compared with the histologic findings at various time intervals after implantation.

6177-42, Session 8

Characterization of malaria infected blood cells by scanning confocal laser and acoustic vector contrast microscopy

E. T. Ahmed Mohamed, A. Kamanyi, Jr., R. Wannemacher, W. Grill, Univ. Leipzig (Germany)

The contrast schemes and characterizable parameters of blood cells, including malaria infected red blood cells have been studied to identify possible detection schemes valuable for disease monitoring. The results of combinatory multicontrast imaging including fluorescence, transmission, reflection, microspectroscopy, speed of sound, acoustic absorption and topographic contrast are demonstrated and analyzed with emphasis on possible medical applications.

6177-43, Session 9

High-resolution ultrasonic imaging system with laser-based generation

Y. Zhou, G. Petculescu, I. N. Komsky, S. Krishnaswamy, Northwestern Univ.

Ultrasonic NDI methods have an impressive record of applications on metal and composite structures. However, two major weaknesses are encountered: the need for a wet couplant between the specimen and the transducer and the rather long inspection times necessitated by point-by-point scanning of large structures. To overcome these limitations, a real-time dry-contact large area ultrasonic imaging system is being developed. This system incorporates three technologies: laser generation of ultrasound which provides focused or large area insonification, polymer dry couplant, and a commercially available real-time ultrasonic imaging system, which will display easy-to-interpret images rather than A-scans. In this paper we present new results on the development and integration of the imaging system components. An optical head has been designed for the imaging system to ensure safe delivery of laser energy. The laser beam is first delivered to the optical head from the laser system via a 1mm optical fiber to be expanded up to 1 inch in diameter. The ultrasound then is generated by the laser beam in a constrained polymer layer, which constitutes the ultrasonic source of the system. This polymer layer is essentially a composite layer of mixed materials, where some of the elements provide enhanced optical absorption while the others provide a large thermal expansion. This soft polymer layer can also work as a dry couplant to efficiently couple the ultrasound between the test sample and the imaging system. Several applications of this real-time ultrasonic imaging system will also be presented. This includes applications on metallic and composite structures including composite with unidirectional and cross-ply laminates, as well as composites with woven cloth. Ultrasonic images acquired in through-transmission mode and pulse-echo mode with ultrasonic signals generated by either piezoelectric transducer or laser based ultrasonic transmitter will be presented. Images of defects of different shapes and varying depths will be demonstrated.

6177-44, Session 9

Scanning acoustic defocused transmission microscopy with vector contrast combined with holography for weak bond imaging

E. Twerdowski, M. von Buttlar, Univ. Leipzig (Germany); M. Pluta, Politechnika Wroclawska (Poland); W. Grill, Univ. Leipzig (Germany)

Surface focused acoustic transmission microscopy is employed for projection (tomographic) imaging of bonded materials including wafers. Short pulse excitation with apodized focusing transducers and two channel quadrature transient detection is employed for multiple contrast imaging. The achievable contrast schemes are based on mode selection for longitudinal, slow, fast, and oblique transverse, mode converted, and scattered modes, as well as imaging in selected echo- and conversion patterns. The identification of the involved modes including conversion schemes is experimentally accessible by observation of spatially selected holograms. Perfect bonding, disbonding, fluid separated disbonding and weak bonding can be studied and characterized by the developed mode selective imaging scheme. The characteristic features of weak bonding phenomena are demonstrated and characterized. The quantitative holographic imaging and identification of the observed contrast modes is based on comparison to modeling of acoustic wave transport in anisotropic media.

High resolution imaging has been performed for frequencies up to 400 MHz.

6177-45, Session 9

Resonant polymeric optical waveguide cantilever for use in 2D scanning

W. Wang, R. R. Panergo, Univ. of Washington

We present SU-8 as an optical waveguide and its integration into a functional 2-D scanner device. The waveguide is fabricated as a tapered structure and cantilever beam (100 *m x 100 *m x 2100 *m). It is mounted onto a coupled bimorph piezoactuator and driven at resonant frequencies of 4.7kHz in the vertical and 25Hz in the horizontal. This raster motion allows for two-dimensional image scanning when in combination with light source and detector. An analysis of the polymer's optical capabilities has shown a coupling efficiency of 71.4% with a propagation loss of 40dB/cm with a wavelength of 633nm. A specific application for the design is in the area of endoscopy where the need for a minimally invasive device reduces the discomfort experienced by the patient. SU-8 as the functional waveguide is the initial phase in creating a Micro-Electro-Mechanical System (MEMS) fabricated device.

Conference 6177: Health Monitoring and Smart NDE of Structural and Biological Systems V

6177-46, Session 9

Scanning contact imaging for transmission acoustic holography of piezoelectric materials

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Electric surface excitation in the Coulomb field of scanned point contacts and similar detection has been employed for imaging of the transport properties of acoustic waves in piezoelectric materials including single crystalline wafers. The employed Coulomb excitation scheme leads to a fully predictable and in addition almost ideal point excitation and detection scheme. Together with precision high resolution two dimensional scanning and short pulse excitation in combination with two channel quadrature transient detection as well as direct full transient detection leads to high precision spatially and temporally resolved holographic imaging. In combination with modeling of the excitation and propagation properties, the effective elastic tensor, as well as the piezoelectric properties of the observed materials can be determined with high resolution from a single image. The generation and detection scheme, applications as well as the theoretical background are demonstrated and applications including such appropriate for industrial demands are exemplified.

6177-47, Session 9

A numerical approach to microwave imaging based on genetic algorithm optimization

S. Noghanian, A. Sabouni, Univ. of Manitoba (Canada); S. Pistorius, CancerCare Manitoba (Canada)

In the past few years microwave imaging has received a great amount of attention due to its versatility and suitability for wide range of applications such as medical diagnostics, nondestructive evaluation and subsurface imaging. Microwave imaging is based on contrast between the dielectric properties of materials. Microwave tomography is a very reliable microwave imaging technique. However, it faces the big challenge of solving a computationally intensive inverse scattering problem. In this method, a set of finitely sampled scattered field is assumed to be measured in a scattering experiment. This measured field is then used to reconstruct the physical parameters of the scatterer including shape, permittivity, and conductivity profiles. The scattered field is nonlinearly related to the scattering object. This means that inverse scattering problems are nonlinear and they are ill-posed because the operator that maps the scatterer properties to the scattered field is compact. In general, the nonlinearity of inverse problems can be dealt with using an iterative optimization method. A cost function, which is related to the difference between the predicted scattered field from an object and the measured field, is minimized.

In this paper a two dimensional cylindrical configurations in the spatial domain is assumed. This model is suitable for breast cancer imaging, which is our primary application. The illumination is done at different angles of view and the scattered electric filed is measured around the circle. After discretizing the solution space, the dielectric properties of the solution domain is used as parameters to optimize the cost function. The optimization is based on Genetic Algorithm (GA). The GA is a popular evolutionary global optimization method that performs very well for problems with high number of parameters and high non-linearity degrees. Finite Difference Time Domain (FDTD) method is employed to compute the scattered electric field at the observation points to provide information needed at each generation of GA optimization procedure. The Modified Perfect Match Layer (MPML) Absorbing Boundary Condition (ABC) is used at the boundary. Realizing that the scattering field calculation must be called tens or even hundreds of times at each generation in the GA procedure, the computation could be very time-consuming. To overcome this problem, in this work a parallel GA/FDTD method is proposed and developed which makes use of Message Passing Interface (MPI) technique to reduce the computation time through clustering and parallel processing. In this technique, the master-slave model is chosen to parallelize the GA.

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6178-01, Session 1

Real-time monitoring of structural vibration using a novel fiber optic accelerometer system

D. H. Kim, M. Q. Feng, Univ. of California/Irvine

This paper presents the use of a novel fiber optic accelerometer system to monitor ambient vibration and seismic response of civil engineering structures in real time. This sensor system integrates the Moiré fringe phenomenon with fiber optics to achieve accurate and reliable measurements. A low-cost signal processing unit implements unique algorithms to further enhance the resolution and increase the dynamic bandwidth of the sensors. There are two major benefits in using this fiber optic accelerometer system for monitoring civil engineering structures. One is its immunity to electromagnetic (EM) interference making it suitable for difficult applications in such environments involving strong EM fields, electrical spark-induced explosion risks, and cabling problems, prohibiting the use of conventional electromagnetic accelerometers. The other benefit is its ability to measure both low- and high-amplitude vibrations with a constantly high resolution without pre-setting a gain level, as usually required in a conventional accelerometer. This benefit makes the sensor system particularly useful for real-time measurement of both ambient vibration (that is often used for structural health monitoring) and strong motion. This paper also presents the prototype development, shaking table tests, and field implementations and demonstrates the uniquely high performance of the Moiré fringe fiber optic sensor system.

6178-03, Session 1

Non-destructive condition evaluation of stress cable using magnetoelastic technology

Y. Zhao, M. L. Wang, Univ. of Illinois at Chicago

High tensile steel wires have many structural applications as individual wires, or in the form of tendons, cables or ropes. These applications include pre-tensioned and post-tensioned concrete bridges and buildings, pipelines, cable-supported bridges and anchors in ground engineering. Structures and facilities deteriorate over a period of years or decades and eventually wear out or become unsafe. Understanding when to replace them and how to prolong their useful lifetime is becoming increasingly important. Observing and/or predicting the onset of dangerous structural behavior, such as hurricane, typhoon, collision and earthquake, can allow for advance warning of such behavior and commencement of mitigating control or removal of the structure from service for the protection of human life. It is clear the ability to continuously monitor the integrity of structures, particularly aging structures in widespread use today, can reduce the cost and downtime associated with repair of critical damage, and provide increased safety for the public in real-time. Magnetic methods are currently the foremost methods for the non-destructive evaluation of steel structures. This paper is focusing on the applications of megnetoelastic technology on condition evaluation of steel tendons for pre/post stressed structures and large bridges.

Many efforts have been made during last decades to develop the reliable NDE methods and instruments for stress measurements and fracture in various materials. The remanent magnetism of magnetized tendons has been used to detect steel fracture. A magnetostrictive- based device has been designed for the detection of defects in long steel cylindrical bars and strand using low-frequency ultrasonic longitudinal guided waves. Based on the same principle, magnetic stray field sensor has been developed to measure force and stress of reinforced concrete elements. In the mean time, Eddy-current sensors have applied to measure the strain and stress of steel reinforced concrete. However, the most prominent NDE technology is the EM sensor which is based on magnetoelastic property of steel cables. EM sensor is a promising technology in real stress monitoring for tendons, steel cables and steel embedded in concrete. Taking measurements non-destructively, it can be moved to any location along the cable; this is especially useful in pre-stressed concrete and cable/suspension bridge applications. In this paper, the authors will introduce and discuss the applications of EM sensor on bridges and steel structures to monitor the force condition of strand and strand bundle, parallel piano wire bundle, and steel bar in detail. Furthermore, as a force sensor, multi-EM sensor configuration has been developed to control, measure and monitor the force distribution in each individual strand in an anchor during and after pulling. This newly developed technology has the ability of detecting strand failure in a cable bundle.

6178-04, Session 1

Evaluation of the quality and stationarity of ambient monitoring data

Q. Pan, K. A. Grimmelsman, A. E. Aktan, Drexel Univ.

The quality of test data is an important consideration in conducting field experiments on civil infrastructure. In addition to possible errors due to the experimental setup, the uncertainties due to incomplete knowledge of a structure's behavior and its interactions with the natural environment greatly affect the reliability of the final results. This paper discusses the uncertainty related to ambient vibration testing of a long-span steel arch bridge. The consistency of the identified parameters is examined through statistical analyses, and the effects of stationarity on the identified parameters are discussed

6178-05, Session 2

Direct substructural identification for online monitoring using acceleration measurements with neural networks

B. Xu, Hunan Univ. (China)

Structural parametric identification has become an increasingly important research topic for health monitoring, damage assessment and safety evaluation of existing infrastructures. Mathematical-model-based structural identification algorithms for civil engineering structures, which are applicable in concept to most structural models, have been proposed in the past two decades. Because actual infrastructures that normally need to be treated as a large-scale system with a large number of degree-of-freedom, response measurement and parametric identification for the whole structure are difficult and the accuracy of estimation is rarely reliable. On one hand, a large-scale structure can be divided to several substructures, and measurement and identification for each substructure may be performed more efficiently. On the other hand, the ability of artificial neural networks to approximate arbitrary continuous function provides an efficient soft computing strategy for parametric identification of structural health monitoring systems. In recent years, most structural identification strategies with neural networks have been proposed to give a qualitative indication of damage using dynamic response measurements or quantitative identification with eigenvalues or eigenvectors. The author developed a serial of identification methods for multi-degrees of freedom structures with the direct use of forced or free vibration induced displacement, velocity measurements without any mode shapes and frequency extraction from the measurements. Since acceleration responses are readily available in real structures, it is desirable to develop acceleration-based algorithms for structural parameters identification. In this study, a direct substructural identification methodology using acceleration measurements with neural networks is developed. The rationality of the proposed substructural identification methodology by the direct use of acceleration measurements is explained and the theory basis for the construction of substructural acceleration-based emulator neural network(SAENN) and substructural parametric evaluation neural network(SPENN) are described according to the discrete time solution of the state space equation of the motion equation of the substructure. An evaluation index called root mean square of prediction difference vector (RMSPDV) is presented to evaluate the condition of object structure. Based on the trained SAENN and the PENN that describes the relation between structural parameters and the components of the corresponding RMSPDVs, the inter-storey stiffness and damping coefficients of a multi-storey shear building structure that is treated as the object structure is identified. The accuracy, sensibility and efficacy of the proposed strategy are also examined by numerical simulations. The performance of the proposed method for incomplete measurement and the influence of measure noise are also discussed. Since the strategy does not require the extraction of structural dynamic characteristics such as frequencies and mode shapes, it is shown computationally efficient, thus providing a possibly viable tool for structural health monitoring of civil infrastructures.

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6178-06, Session 2

Multiscale analysis of material damage in civil infrastructure using embedded microsensors

L. Sun, M. Shinozuka, Univ. of California/Irvine; X. Li, Univ. of Wisconsin/Madison

Research and development related to homeland security has emerged as one of the most challenging topics nationwide in the recent few years. Effective structural health monitoring, diagnosis and prognosis are of importance for the safety and reliability analysis of civil infrastructure systems. With distributed microsensors embedded into a sufficient set of hot-spots in civil structures, we aim to analyze material damage and structural safety and reliability. The sensors can survive hostile environments and provide high accuracy, long-term stability, and good reliability during service. They can be designed for either dynamic or static measurements with various patterns. The multiscale methodology for material damage of civil structures is developed based on multiscale physics with microstructure and macrostructure integration. Micromechanics-based damage mechanics framework is modeled with respect to fatigue damage to evaluate the overall performance of the material system. Uncertainties are taken into account from material microstructures and external loading states. This multiscale analysis is able to build a link between the damage state and specific patterns of the output strain signals of the embedded sensor network.

6178-07, Session 2

Nondestructive testing methods in deep foundation engineering accident treatment

Z. Li, Parikh Consultants Inc.; Q. Cheng, Sr., Shenzhen Civil Engineering Testing Ctr. (China)

The roles of low strain dynamic testing for pile structural integrity evaluation and high strain dynamic testing for pile bearing capacity evaluation in finding hidden engineering problems were introduced in this paper through a typical case of deep foundation engineering accident.

The pre-cast concrete pile foundation with 284 piles was used for a 12-story student dorm building. The design length of the pile is 19m. For the convenience of construction, the piles were cast in two sections, 9m for top section and 10m for bottom section. The designed ultimate bearing capacity of single pile was 1000kN. Based on the testing program designed for this project, 85 piles were chosen randomly for structural integrity testing using low strain dynamic testing one month after the completion of pile driving. The testing results showed that most of the stress wave curves achieved have strong same phase reflection at the connections of the two sections, which means there are serious problems at the pile connections. To verify the conclusions and further clarify the degree of the problems, high strain dynamic testing method was chosen to evaluate the bearing capacity. 10 piles selected based on previous testing results for bearing capacity evaluation. High strain dynamic tests were performed using Pile Driving Analyzer (PDA) by drop weight method (350kN). To find out if there is horizontal displacement existing between two sections of the pile, 4 to 6 strikes were performed for each pile during the test. After 4 to 6 strikes, most of the testing piles were observed to have 5 to 10cm settlement on the top of the pile. The testing results were analyzed using CAPWAP method. In general, the testing piles have 380 to 480kN static bearing capacity for the first 2 strike and 900 to 1250kN static bearing capacity for the last strike. The testing results have given a clear picture of this accident: 1) the two sections of the pile are disconnected with 5 to 10cm vertical distance after pile driving; 2) the two sections of the pile have no horizontal displacement.

The first step of the treatment of this accident was to perform low strain dynamic testing on every engineering pile to find which of them has the structural integrity problems. High strain dynamic testing was then used to re-position the top section of the piles and evaluate the bearing capacities. As requested by the owner, all the piles after re-position were then tested using low strain dynamic testing method. And the there are no strong same phase reflection at the connection in the tested stress wave curves.

The diagnostics and treatment of this accident have shown that non-destructive testing methods can play very important roles in foundation engineering. Low strain dynamic testing, which is cheap and very easy to perform, can be applied on a large amount of engineering piles. High strain dynamic testing, which is more expensive but can provide more information, can be used to verify and further find the causes of the engineering problems. Efficiently and economically using the combination of these two methods can get best results in deep foundation engineering.

6178-08, Session 2

Development of a diagnostic/prognostic system (DPS) for monitoring the performance of repaired composite military bridges

A. S. Mosallam, Univ. of California/Irvine

The paper describes the details of an innovative Diagnostic/Prognostic System (DPS) for monitoring the performance and reliability of a smart repair kit (SRK) for composite military bridges. The DPS system is founded on three technologies, namely; optical fiber sensing, remote data transmission and virtual testing. In developing this system, both laboratory and virtual tests simulating the different potential damage scenarios. In order to minimize the number of expensive full-scale tests, virtual testing technique using an advanced progressive failure simulator code (GENOA) was utilized. The results of the pre-simulated damage scenarios are stored in a secure database. Different composite patches with optical fiber sensors are being developed for different damage types. These smart patches act as health-monitoring devices for different parts of the composite bridge, especially areas surrounding the repaired portions of the bridge. In the event of local damage such as debonding of any patch due to excessive loading or lower application quality, for example, the stress distribution will change. This change is reflected by a sudden change in the fiber optic sensor readings. The peak field data is transmitted instantaneously and continuously to both the bridge launcher as well as the army base command unit. The information is transmitted remotely via an army secured satellite system and collected in a secured army web server that contains the pre-simulation database. In order to translate the complex stress variation information to the Army bridging unit operators, simple charts indicating the expected stress levels, with and without the composite batches are prepared. These simple-to-read charts will be developed using post-processed simulated results obtained from the GENOA software. A family of curves will thus be generated, providing a simple detection tool for possible damage(s) of hidden parts.

In the actual battlefield, the signals will be transmitted to the bridge launcher and transporter control panels as well oncoming tanks and other military vehicles in the form of clearance or warning signals such as a color code (e.g. Red - Do Not Cross, Orange - Crossing is limited to certain MLC loads, Green - Safe to Cross). This instantaneous and continuous clearance and warning system can facilitate rapid combat maneuvering by providing the oncoming troops with bridge status and enabling early selection of alternative routes if needed. The information is stored in the bridge transporter or support vehicle's computer and is used as a reference for future battlefield emergency repairs as well as during the non-combat depot repair and maintenance procedures. The proposed technique will provide the base personnel with continuous and current information on the overall performance of their composite bridge(s). The transmitted information will enable the base engineering personnel to assess the damages and the performance of a number of bridges at different battlefield locations resulting in instantaneous instructions, assistance and recommendations to the bridge operators and engineers at the battlefield via Internet connections.

6178-09, Session 2

Intelligent structures with sound and damage detection capabilities

A. Kumar, S. J. Beard, P. Qing, Acellent Technologies, Inc.

Acellent Technologies is developing innovative structural health monitoring (SHM) sensor network systems that can autonomously assess in real time the structural stability of structures such as buildings. The sensor network will use a combination of large and small piezoelectric actuators and sensors to characterize damage in, and monitor the rigidity of components of the building primary structure, and fiber optic temperature sensors to monitor the structural temperature at various locations in the building. Innovations include novel sensor/actuator arrangement, the integration of fiber optic temperature sensors and software that will provide a map of the structural damage, rigidity and temperature information that can be used to provide a real time assessment of a building's structural integrity. An additional development is to use the sensors to recognize sound and/or voice transmitted through the structure to allow search and rescue personnel to pinpoint the location of survivors and determine what they are trying to say through an easy conversion to text messaging. This presentation will focus on the concept of the development and how it can be applied to homeland security.

6178-10, Session 2

Broken rail track detection using smart materials

D. J. Inman, B. L. Grisso, Virginia Polytechnic Institute and State Univ.

Rail lines are subject to damage of all sorts including terrorism. This paper focuses on a simple proof of concept experiment to determine if impedance based structural health monitoring may be used to determine anomalies in rail tracks, and in particular broken rails. The methodology is to apply a very low voltage (one volt) high frequency (50 kHz) wave to a structure, measure its response and determine the location and extent of a rail break. This device will run off of ambient vibration and thermal gradients provided by passing trains and daily thermal cycles, store the energy and release it periodically to inspect the track (according to the track usage schedule). If damage occurs or starts to occur, a warning signal would be transmitted to substation then broadcast to the appropriate operator listing the location and extent of the damage.

6178-11, Session 3

Real-time damage localization by means of MEMS sensors and use of wireless data transmission

M. Shinozuka, C. Park, P. H. Chou, Y. Fukuda, Univ. of California/Irvine

Use of densely installed MEMS sensors and wireless transmission of measured data makes it possible to identify location of the damage and assess the extent of damage, when lifeline systems such as water delivery networks are monitored with densely populated MEMS sensors with optimally located wireless nodes transmitting data. Transient analysis of water pressure in the networked pipes showed that the damage sustained by the pipe create a state of transient in the pipe pressure which is detected by MEMS sensors for damage localization and estimation. This is critical information to enhance post-event disaster mitigation.

6178-12, Session 3

Centralized web-based loss estimation tool: INLET for disaster response

H. Chung, R. T. Eguchi, C. K. Huyck, S. Cho, ImageCat, Inc.

A Centralized web-based loss estimation and transportation modeling platform, entitled INLET for Internet (based) Loss Estimation Tool, is built to test and evaluate the efficacy of Information Technology (IT) solutions in reducing the impacts of natural and human threat events on transportation systems. This development was taken place in a large NSF-sponsored research program called RESCUE (Responding to Crises and Unexpected Events). The ultimate goal of this research is to assist government officials in effectively managing disasters using new and emerging information technologies. The loss estimation system that is being development by ImageCat Incorporates a Geographical Information System (GIS) component, unlimited internet accessibility, a risk estimation engine, and a complex transportation simulation engine. When combined, these elements provide a robust online calculation capability that can estimate damage and losses to buildings and critical transportation infrastructure in real time during man-made or natural disasters. A prototype of this internet web-based program has been developed using JAVA computer codes, the University of Minnesoda's Mapserver software, and a PostGRE SQL database with a PostGIS Spatial component. The basic component of this system have been tested and validated in the calculation of building losses, damage of transportation systems and casualties for a series of historic earthquake events in Southern California.

6178-13, Session 3

Remote sensing for building inventory update and improved loss estimation in HAZUS

H. Chung, C. K. Huyck, B. J. Adams, ImageCat, Inc.

HAZUS(r) (HAZards-US) is a desktop loss estimation program developed by FEMA under agreements with the National Institute of Building Sciences. HAZUS(r) estimates disaster-related losses using default building stock data derived from the census and commercial databases. Although this may provide a fairly accurate portrait of building stock for an entire region, the spatial variation of structural types within the region is poorly characterized. This is particularly evident in census tracts with high-rise structures. This study examines the use of remotely-sensed data to supplement default HAZUS(r)99 databases. The underlying HAZUS(r)99 building stock tables were adjusted using square footage and height data derived from airborne SAR (Synthetic Aperture Radar) and optical imagery. An automated program generated a suite of the "mapping schemes" that characterize structure type by occupancy. While the mapping scheme default is generally used to characterize a region as a whole, in this case a separate scheme was created for each census tract within the Los Angeles County study region. For comparative purposes, per-census tract mapping schemes were also derived from tax assessor's data. Comparing HAZUS(r)99 results obtained using the default, imagery-derived, and tax assessor-derived mapping schemes demonstrates that remote sensing data is a useful source for updating the square footage database. Square footage estimates from remotely sensed data are on par with HAZUS estimates, but both over estimate Tax Assessor square footage. The remotely sensed data provides a more accurate estimate of building height for areas with high-rise structures. These preliminary findings suggest that remotely-sensed data may be useful for loss estimation studies internationally where building stock data may not be available, and for studies which focus on highly developed urban areas.

6178-14, Session 3

Performance monitoring of the Geumdang bridge using a wireless mnitoring system

J. P. Lynch, Univ. of Michigan; Y. Wang, Stanford Univ.; K. J. Loh, Univ. of Michigan; J. Yi, C. Yun, Korea Advanced Institute of Science and Technology

Structural monitoring systems designed using wireless sensors have shown the potential to serve as low-cost substitutes to traditional cabled-based monitoring systems. In this study, an academic wireless sensing unit prototype explicitly designed for structural monitoring is introduced. To validate the performance of the proposed wireless sensing unit prototype, a large-scale network of over 14 units is installed in the Geumdang Bridge, Icheon, South Korea. The installation of the wireless sensor network is rapid and is performed in less than 1 hour. In parallel to the wireless monitoring system, a traditional tethered structural monitoring is also installed. The acceleration response of the Geumdang Bridge concrete box girder is recorded by both monitoring systems during forced vibration testing. In particular, various trucks are driven over the bridge at controlled speeds. The measurement fidelity of the wireless monitoring system is shown to be sufficiently accurate for precise determination of the primary modal frequencies and operating deflection shapes of the bridge. With wireless monitoring systems employing individual clocks distributed across its network, clock synchronization is performed using a centralized beacon signal. Using response data synchronously recorded by the tethered monitoring system, the synchronization error present in the beacon signal clock synchronization strategy is assessed. In the last phase of the field study, the wireless sensing units are programmed to locally process their measurement data using an embedded fast Fourier transform algorithm.

6178-15, Session 3

A laboratory demonstration of a wireless structural data collection system

A. S. Kiremidjian, Stanford Univ.; G. K. Kiremidjian, P. Sarabandi, D. Perry, B. Benco, Sensametrics, Inc.

A new wireless structural data collection system was deployed by Sensametrics, Inc. to enable early testing of the wireless structural monitoring system currently under development. The data collection system utilizes small units that are equipped with accelerometers capable of measuring vibrations over a wide range of frequencies (0.05 to 50Hz) and accelerations between 0.25mg and 5g in the x, y and z-directions. The units are remotely triggered and synchronized and data are collected, stored on a microcontroller and a flash memory chip and then transmitted wirelessly to a laptop.

The system was tested on a near-full scale bridge column subjected to earthquake motions. The load on the column was successively increased until failure was reached. The wireless system was triggered with each test and data were collected demonstrating the capabilities of the system. The data collected with the Sensametrics system was compared to data collection by a conventional wired system also installed on the column.

The data collection system is a predecessor to the system currently under construction which will have expanded sensing capabilities, more complex wireless networking protocol and a decision support system that can serve various functions.

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6178-16, Session 3

Man-portable high power generation device using magnetostrictive elements

L. M. Twarek, A. B. Flatau, Univ. of Maryland/College Park

The increased use of electronic devices in military and paramilitary applications has drastically changed the way modern conflicts are carried out. However, certain new and improved technologies require a large amount of electrical power over a short duration. While modern battery and fuel cell technologies are able to supply moderate amounts of power for extended periods of time, their capacity for high power, short duration - or 'burst' power - is limited. Classically, a large capacitor is used in burst power applications. However, large value capacitors have numerous drawbacks including the need to be charged before use. Also, the single-shot nature of discharging a capacitor means that, unless a charging source is included, the device will have a one-time use. Additionally, the dangers associated with transporting a charged large value capacitor are both extreme and numerous. Thus, an attempt is made to develop an alternative means to generate burst power from a compact, man-portable, robust, low-maintenance, reusable device. One such device would harness the magnetomechanical coupling in magnetostrictive smart materials. By imparting a mechanical force on a magnetostrictive element, a comparatively large change in the magnetization state of the element occurs. This change in magnetization produces a change in the total magnetic energy of the system. This change in magnetic energy can then be harnessed by a solenoid with the magnetostrictive element at its core and converted into electrical energy. If this force were applied very rapidly, such as due to impact or an explosion, a shock wave would propagate through the magnetostrictive element at the speed of sound in the material. This extremely quick change in the magnetization state of the material would result in burst power generation. Theoretical work suggests a relatively small magnetostrictive element (0.25 in x 0.25 in x 2 in) could produce on the order of 3 kilowatts of burst power. Choosing the correct magnetostrictive element for this application is critical. Multiple use requirements would dictate that the material have a high modulus of toughness, while maximum available magnetic energy would necessitate a high magnetic relative permeability. Magnetostrictive alloys of Gallium and Iron, collectively know as Galfenol, possess both high permeability and one of the highest modulus of toughness of any smart material. Practical considerations include the magnetomechanical coupling efficiency of the magnetostrictive element, electromagnetic conversion efficiency of the solenoid, and prevention of eddy current formation in the magnetostrictive element. Experimental work in both impact and detonation forcing of the magnetostrictive element are completed to verify theoretical model.

6178-17, Session 4

Dual-energy detection of weapons of mass destruction

M. C. Barker, Varian Medical Systems, Inc.

Introduction:

Dual energy imaging is a technique that makes it possible to determine the make-up of a scanned object by exploiting differences in how the scanned material interacts with X-rays with different energies. The process involves taking two X-ray projection images of the same object using X-ray spectra with different end point energies and extracting information about the atomic composition of the X-rayed material. The process works because, in some energy ranges, X-rays interact via two different physical mechanisms related to the atomic number of the scanned material. By making two measurements, a dual energy system can determine the effective atomic number of the material being X-rayed.

The first practical use of dual energy imaging occurred in medical settings. It was used to create separate images of bone and tissue in chest imaging. In the late '70s and early '80s, this quickly became a common medical technique. It also became common for measuring bone density.

The practical implications of dual energy imaging were also apparent to engineers in the security industry, who adopted it as a standard for airport X-ray scanners. Initially it was used to create separate images of metallic items inside luggage (to reveal hidden hard weapons, guns, knives, etc.). Later it was used to identify plastic explosives automatically in baggage1.

There has been ongoing interest in extending this technique to high-energy scanning. Experiments were conducted by Cambridge Imaging Ltd, and the Police Scientific Development Branch2 in the UK showing a limited capability for dual-energy imaging using very sophisticated detector arrays. Experiments by Ogorodnikov and Petrunin3 using interdigitated 8 and 4 MeV X-ray spectra showed that there is clearly a dual-energy effect that can be measured, but also that the statistical errors in determining the atomic number of the material being X-rayed are so large that the technique is of very limited utility. So until recently there has been little interest in implementing this technique at high X-ray energies.

Problem Definition:

The attacks of 9/11 have forced a reconsideration of our vulnerabilities and technologies that can mitigate them. One area of great concern is the possible importation of weapons of mass destruction (WMDs) or radiological dispersal devices (RDDs or dirty bombs) in a sea cargo container. Even a relatively small event could cause a disruption of world commerce that would have a staggering economic impact.

The X-ray inspection process and the possible use of dual-energy imaging should be considered to interdict materials for WMDs. There are several major characteristics that one can hope to exploit for the detection. First, both WMDs and RDDs are radioactive. Therefore, one can hope to detect radiation coming from the containers to identify the threat. However since uranium and plutonium are largely self-shielding and since lead can be used to shield and hide these substances, passive detection of emitted radiation can be easily defeated.

An important second characteristic is that WMDs and shielded dirty bombs contain materials with very high atomic numbers. Since normal commerce rarely contains materials with atomic numbers higher than that of iron, dual-energy imaging technology could be used to detect such materials automatically, for the successful interdiction of WMDs and dirty bombs.

In a previous paper we have discussed the theory of using dual-energy imaging to automatically detect WMDs. In this paper we describe a simple experiment to verify this technique.

6178-18, Session 4

Integrated systems technologies for homeland security applications

E. S. Andersen, Pacific Northwest National Lab.

As more and new technologies are introduced for use in Homeland Security, the need exists for integrated systems. Technologies such as interdiction systems, visual identification systems, traffic control systems, communications, video surveillance systems, network systems for data communications between the local integrated systems and to remote servers, all need to be integrated for streamlined functionality. Implementation of these technologies requires significant manpower allocations as well. With limited resources for staffing, some of these systems will also need to be operated from a location other than where the system is actually being used. This paper will describe some of the issues being addressed today at the Pacific Northwest National Laboratory, some of the systems being integrated and why, and some of the lessons learned from real field installations.

6178-19, Session 4

NDE of RCC wing leading edge panel using Digitome volumetric

T. P. Chu, Southern Illinois Univ. Carbondale

The feasibility of using Digitome X-ray Volumetric Image System as an NDE tool for inspecting space shuttle wing leading edge (WLE) was studied. The Digitome system is capable of generating XY-cuts (horizontal) and Z-cuts (vertical) of the object being examined. Basically, the system is calibrated first using the x-ray image of a calibration post and markers. The x-ray images of the object are then taken while the object is rotated through several preset positions with equal angle between adjacent ones. Finally the XY and Z cuts of the object are created and measured. The Digitome system is setup in an x-ray cell and is integrated with the X-ray source and the Varian PaxScan 2520 flat panel detector. Tests were conducted on an aluminum block with two countersunk holes and RCC panels with test holes. Three different configurations were used during the tests. The results show that, for the aluminum block, the setting with 16 stops and 22.5 degree intervals produces the sharpest and most clear cuts. A RCC panel was tested using this 16-stop configuration. The width and depth of the center hole were measured using Z-cut. The measurement of the diameter has a 2% error. However the measurement of the depth of the hole has 30% error. In summary, it is found that Digitome system is capable of reconstructing volumetric images and measuring internal features. More work will be needed to fine tune the techniques of depth measurements.

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6178-20, Session 4

Structural health assurance by in-situ chemical analysis

M. Ghandehari, Polytechnic Univ.

Degradation processes in materials and structures are often catalyzed by, or accompanied by chemical reactions. Direct monitoring of such chemical processes, in advance of the emergence of the corresponding physical damage, is an effective means of enhancing infrastructure safety and serviceability. Complementing existing knowledge of materials performance, which is based on historical patterns and theoretical principles, real time in-situ chemical analysis is instrumental in improving practices of materials health management. This presentation describes the concept of real time in-situ chemical analysis in civil infrastructure materials using embedded optical fiber probes.

6178-21, Session 4

Advanced ultrasonic measurement methodology for noninvasive interrogation and identification of fluids in sealed containers

B. J. Tucker, A. A. Diaz, Pacific Northwest National Lab.; B. A. Eckenrode, Federal Bureau of Investigation

The Hazardous Materials Response Unit (HMRU) and the Counterterrorism and Forensic Science Research Unit (CTFSRU), Laboratory Division, Federal Bureau of Investigation (FBI) are responsible for developing and establishing a wide range of unprecedented capabilities for providing scientific and technical forensic services to investigations involving hazardous chemical, biological, and radiological materials, including extremely dangerous chemical and biological warfare agents. Pacific Northwest National Laboratory (PNNL) has developed a portable, handheld, hazardous materials acoustic inspection device (HAZAID) that provides noninvasive container interrogation and material identification capabilities using nondestructive ultrasonic velocity and attenuation measurements. Due to the wide variety of fluids as well as container sizes and materials, the need for increased measurement sensitivity and more advanced ultrasonic measurement techniques were identified. Advantages of the new techniques and their incorporation into the new portable unit will be presented.

6178-22, Session 4

Cantilever-based measurement set-up for electromechanical property characterization in polymeric fiber

T. Xu, National Institute of Aerospace; J. Su, K. J. Pawlowski, E. J. Siochi, NASA Langley Research Ctr.

Electroactive polymeric fibers with sensing and actuation capabilities can be used for many aerospace applications , such as robotics, electrically responsive wing skins for micro air vehicle wing frames, actuators for dynamic controls, and biosensors. However, the characterization of electromechanical properties in a polymeric fiber is still a challenge for scientists. We recently developed a cantilever based measurement set-up for electromechanical property characterization in polymeric fibers at NASA Langley Research Center. This set-up measures electrostriction and piezoelectric constants in a polymeric fiber simultaneously. The performance of the set-up was theoretically and experimentally evaluated. The detail of the set-up and its performance will be presented in this talk.

6178-23, Session 4

Future roles of structural sensing for aerospace applications

M. M. Derriso, Air Force Research Lab.; F. Chang, Stanford Univ.

The Department of Defense (DoD) is continuously evaluating different methodologies to reduce cost, increase availability, and maintain safety of current and future air vehicle systems. Recently, emphasis has been placed on the development of Integrated Systems Health Management (ISHM) techniques. The ISHM process provides the appropriate architecture to determine system level health based on combined assessments of the various subsystem conditions and, as necessary, interacts with flight control systems to ensure mission success. Since the vehicle structure is one of the most critical subsystems, structural health monitoring (SHM) techniques are being developed. These SHM techniques offer unique benefits for both fielded and emerging air vehicle systems. For fielded vehicles, a major sustainment cost driver in the air vehicle fleet today is unscheduled maintenance. By utilizing SHM techniques, DoD intends to migrate to condition-based maintenance instead of the current schedule-based approach. Condition-based maintenance will enable DoD to meet its objective of improving maintenance agility and responsiveness for quicker turnaround times, increasing operational availability, and reducing life cycle total ownership cost. Emerging air vehicle systems will likely utilize advanced materials and advanced structural concepts. Extensive use of composite materials is expected and, to further complicate matters, the composite structures also may include embedded electronics or sensors. Advanced structural concepts include techniques such as morphing structures, which will be integrated with other vehicle systems such as the flight controls. As a result, assessing the current state of these structures will be critical. Applications for emerging air vehicle structures offer the potential to consider SHM in the design process, rather than having to retrofit a SHM system to an existing structure. The current paper discusses the future role of SHM for air vehicle applications.

Conference 6179: Advanced Sensor Technologies for NDE and Structural Health Monitoring II

Wednesday-Thursday 1-2 March 2006

Part of Proceedings of SPIE Vol. 6179 Advanced Sensor Technologies for Nondestructive Evaluation and Structural Health Monitoring II

6179-01, Session 1

Advanced ultrasonic inspection technology for anisotropic materials for lightweight constructions

M. Kröning, A. Boulavinov, Fraunhofer-Institut für Zerstörungsfreie Prüfverfahren (Germany); K. M. Reddy, Quality Network Pvt. Ltd. (India); D. Joneit, Fraunhofer-Institut für Zerstörungsfreie Prüfverfahren (Germany)

shall be submitted later, directly to chair

6179-02, Session 1

Advanced imaging of hidden damage under aircraft coatings

A. T. Cooney, J. L. Blackshire, Air Force Research Lab.

The external coating systems of nearly all military aircraft are stripped to bare metal during programmed depot maintenance cycles. This paint stripping process has become cost prohibitive in recent years, and is expected to continue to be a major and escalating problem for the sustainment of an aging Air Force fleet. Although a number of competing factors come into play, the key reason behind current paint stripping practices is centered on requirements for visual inspection of the aircraft structure to determine if corrosion and/or fatigue damage is present. In recent years, a number of advancements have been made in the area of nondestructive evaluation (NDE) that provide new inspection capabilities for aircraft skins without the requirement for protective coating removal. In this effort, several advanced imaging methods are evaluated for hidden damage detection and quantification through typical aircraft coating systems. A number of measurement examples are provided for engineered and realistic aircraft reference standards with variations in coating type, coating thickness, hidden damage type, and component complexity being considered. A comparison of measurement sensitivity, resolution, area coverage, ease-of-use, quantitative assessment, data processing requirements, and inspection speed are also made. It is anticipated that the use of one or more of these advanced NDE methods for thru-paint inspections will provide an enabling capability for long-life coating systems and condition based maintenance practices resulting in significant reductions in hazardous waste generation, dramatic cost savings, and enhanced readiness levels for a wide variety of Air Force systems.

6179-03, Session 1

Acoustic thermography using an uncooled high-speed camera and low-power ultrasonic excitation: test system and its application to impact flaw detection in CFRP

L. Haupt, Fraunhofer-Institut für Zerstörungsfreie Prüfverfahren (Germany); M. Zimmerhackl, DIAS Infrared GmbH (Germany); N. G. Meyendorf, B. Köhler, Fraunhofer-Institut für Zerstörungsfreie Prüfverfahren (Germany)

Acoustic Thermography is a new method for NDE of material flaws, based on thermographic detection of dissipated ultrasonic energy. The test system presented is using an un-cooled high-speed camera and low power ultrasonic excitation. This technology is characterized by low system costs, since no nitrogen or stirling cooling is necessary. Low power applications are facilitated by efficient ultrasonic coupling, hence taking care of sensitive objects. A camera has been developed which uses a 384 x 288 pixels micro-bolometer array as sensor and may record up to 200 frames per second.

The advantages of this system are demonstrated on a set of carbon fiber reinforced plastic plates damaged by impacts of various strengths. The impact flaws consisting of fiber fractures and delaminations can be detected while transmitting low ultrasonic energy of about 1.3 W to the specimen.

6179-04, Session 1

Experimental demonstration of using nanophotonic crystal sensor systems for submicron damage detection, quantification, and diagnoses

M. P. Sheyka, M. F. Su, M. R. Taha, The Univ. of New Mexico; I. F. El-Kady, S. S. Mani, J. G. Fleming, Sandia National Labs.

The premise of implementing intelligent damage detection systems is to provide early warning of damage in critical infrastructures (e.g. sensitive storage tanks, nuclear establishments, etc.) and also potentially to inform authorities about the location, nature and severity of this damage. The major limitation of current structural sensing systems (e.g. accelerometers, piezoelectric sensors, etc.) is that they are incapable of detecting micro-scale damage due to their limited sensitivity. This renders impossible the early detection of potential problems. In this work we present an integrated micro-damage detection approach based on nano-photonic crystal sensors potentially capable of detecting such defects.

Photonic crystals (PC) are engineered structures with a periodicity in the dielectric function. These crystals have the novel ability to mold and control light in three dimensions by opening a frequency region (bandgap) in which light is forbidden to propagate. When correctly designed and fabricated, such structures can exhibit the property that photons with the band gap energy can not penetrate the lattice regardless their angle of incidence. The spectral signature of such crystals is thus intricately tied to their underlying crystal lattice structural parameters. Because of this, there can be large spectral changes when stress induced strains or defects are generated within the bulk of the lattice. This allows these crystals to detect structural changes on the sub-micron length scale in a substrate on which they are mounted.

In this work we present preliminary experimental results on utilizing such a nanophotonic sensor for detection, quantification and diagnoses of sub-micron damage. Matching theoretical predictions for the observed variation in the reflection spectrum and the corresponding damage metric are also presented and discussed. Detailed fabrication steps as well as advantages and limitations of this new approach are also addressed.

6179-05, Session 1

Nondestructive evaluation of ceramic materials using terahertz impulse ranging

M. T. Reiten, R. A. Cheville, L. Hess, Oklahoma State Univ.

Terahertz (THz) impulse ranging is used to nondestructively examine ceramic bodies for fractures. This technique uses optoelectronically generated pulses of terahertz radiation. The resulting pulse is near single-cycle and on the order of picoseconds in duration. Many dielectric materials, including many common industrial ceramics, are transparent to electromagnetic radiation at THz frequencies even when opaque or highly diffusive at optical frequencies. This transparency leads to a potential method to nondestructively detect structural defects in a wide range of previously characterized dielectric materials by exploiting the time domain response. The short THz pulses allow contributions to the scattering signal to be isolated and identified in the time dependent measurements. Fracture detection is demonstrated by evaluating both green body and commercial ceramic products. Two separate methods are used to determine the presence of fractures: late time impulse response (LTIR) and a time domain angular modulation (TDAM) technique. LTIR detects changes in temporally shifted scattering mechanisms. Green bodies are measured in transmission as well as reflection to detect subsurface defects. Comparisons are made between green state and fired ceramic structures. TDAM allows rapid detection of fractures, but is limited to objects with radial or spherical symmetry, such as ceramic bearings. The electromagnetic scattering signature of commercial aluminum oxide ball bearings is measured and compared to identical bearings damaged by thermal stress using both LTIR and TDAM. These evaluation techniques are non-contact, require no liquid medium, and are insensitive to ambient temperatures, such as those occurring during the sintering and firing processes.

6179-06, Session 1

Barkhausen in Dresden: great past and new applications of his discoveries

J. Schreiber, I. Altpeter, N. G. Meyendorf, Fraunhofer-Institut für Zerstörungsfreie Prüfverfahren (Germany)

The year 2006 will commemorate two important life data of Heinrich Barkhausen. 125 years ago, he was born on December 2, 1881, in Bremen. After 55 years of fruitful scientific and educational work at the former Royal Saxon Technical College Dresden, he died on February 20, 1956. These anniversaries are good reason

to remind of the discovery of Barkhausen noise in 1919, which is still the basis for a widely used non-destructive testing method to characterize internal stresses, texture and the hardness of materials. Its physical foundations will be discussed and important practical applications in NDE will be exemplified.

The knowledge of the residual stress state at critical places, e.g. for fatigue loaded steel constructions and sensitive automotive components, is crucial for evaluating and assuring the reliability of these systems. Also during manufacture of tools, residual stresses arise from surface processing, which can harm tool quality. To meet the needs for non-destructive testing in such applications, Fraunhofer IZFP has developed a technique called "<b\>M</b\>icromagnetic <b\>M</b\>ultiparameter <b\>M</b\>icrostructure and Stress <b\>A</b\>nalysis" (3MA-method). Quantitative determination of stress values and other parameters like hardness requires a calibration of the electromagnetic measuring quantities for the investigated material.

The basic principles and applications in the automotive industry, in the sheet metal production and for power station components will be discussed. An approach is presented that is based on a new calibration procedure and allows determining 2D-stress states, e. g. residual stresses for turbine rotors and wind power plants. The residual stress components at the surface of a component are derived from Barkhausen noise amplitudes, which are measured for two perpendicular magnetization directions. By applying a newly developed sensor, which permits to turn the direction of the magnetizing field electronically, a systematic investigation of 2D-stress and texture states can be accomplished. Results are presented for such sensors which can be integrated in the metal forming process.

The outlook refers to new applications of the Barkhausen noise effect. Utilizing cognate noise effects, e.g. the potential noise is stimulated by periodic current excitation, discloses new application fields. Promising results are furthermore obtained by evaluating the fatigue damage and residual service life on the basis of a fractal analysis of the Barkhausen noise signals as a measure of the deformation structures.

6179-07, Session 1

An integrated numerical approach for microdamage detection using nanophotonic sensors

M. P. Sheyka, M. F. Su, The Univ. of New Mexico; I. F. El-Kady, Sandia National Labs. and The Univ. of New Mexico; M. R. Taha, The Univ. of New Mexico

Nano Photonic Crystals (NPC) are synthetic materials that artificially manufactured at the nano-scale to control light propagation. These crystals have the ability to control light propagation in three dimensions by opening a frequency gap in which light is forbidden to propagate. When light is reflected of a photonic crystal a spectral signature that is directly related to its crystalline structure periodicity of the can be observed. It is suggested here that microscale damage in a substrate attached to the NPC sensor might result in a significant change in the spectral signature of the NPC sensor, hence allowing for micro-scale damage detection and quantification.

To demonstrate the use of NPC sensors for microdamage detection in structural materials a integrated numerical modelling approach was used. The approach augments two numerical methods to simulate the effect of microdamage in the material substrate on the spectrum signature of NPC sensors. First, the finite element method (FEM) was used to simulate structural response of the NPC sensor under strain induced in the substrate with and without substrate damage. Second, the results of the finite element analysis were used as inputs to simulate the optical response of the NPC sensors using the finite difference time domain method (FDTD).

The integrated numerical approach was applied to a wood pile NPC sensor attached to a silicon substrate. The numerical analysis showed promising results. Changes in the NPC spectral signatures due microdamage in the silicon substrate were successfully identified.

6179-08, Session 1

Technological assessment of sensing systems in propulsion systems in high-temperature zones

A. Ghoshal, United Technologies Research Ctr.; H. S. Kim, Inha Univ. (South Korea)

Presently there exists no way for direct measurement of strain at high temperature in engine components such as combustion chamber, exhaust nozzle, propellant lines and turbine blades and shaft. Existing fatigue and life prediction studies for high temperature zones in propulsion systems depend on strain/stress values computed from indirect measurements of temperature, flow velocity, pressure, et al. Thermomechanical fatigue (TMF) prediction, which is a critical element for blade design, is a strong function of the temperature and strain profiles. Major uncertainties arise from the inability of current instrumentation to measure temperature and strain at the critical locations. This prevents the structural designer from optimizing the blade design high temperature environment, which is a significant challenging problem in engine design. Ability to measure directly strains in different high temperature zones would deeply enhance the effectiveness of aircraft propulsion systems for fatigue damage assessment and life prediction. State of the art for harsh environment high temperature sensors has improved considerably for the past few years. This paper lays down specifications for high temperature sensors and does the technological assessment of these new sensing technologies. This paper presents a review of the recent advances made in harsh environment sensing systems and takes a peek at the future of such technologies.

6179-09, Session 1

A room-temperature operated fast-response humidity sensor

A. Salehi, A. Nikfarjam, D. Jamshidi kalantari, K.N. Toosi Univ. of Technology (Iran)

A fast response humidity sensor was developed for applications in Microsystems for diagnosis of pulmonary diseases. In this study we deposited Au/Porous GaAs and used the contact as a gas sensor. Due to very low operating temperature of Au/Porous-GaAs Schottky contact which shows rapid response to humidity, it can be a good candidate for humidity sensing applications.

In most of the sensors, selected gas react with the metal and change the metal work function which cause changes in schottky barrier height affecting the I-V characteristics. This is mostly a high temperature process which involves the chemical reactions. The main problem in above methods is their high operating temperature and slower responsivity.

In our samples the gas detection mechanism is different and involves the internal dipole moment of gases which affect the electric fringing fields. Humidity is a dipole gas. There is some saw tooth (because of the porous) in Au/Porous GaAs which has high electric fields and have important effect on reverse voltage (specially in breakdown voltage). When humidity affect the sensor it forms dipole moments which cause some changes in the electric fringing field affecting I-V characteristics. Also poreses in our sensor (Au/Porous GaAs) are so important in sensivity of sensor. We compared different schottky contacts Pd/Porous GaAs and Ag/Porous GaAs and Au/GaAs in humidity sensing applications. We can conclude that Au/Porous GaAs shows much higher responsivity to humidity at low operating voltage and room temperature. We are continuing the research on these bases.

6179-10, Session 2

Guided waves for SHM application

B. Frankenstein, F. Schubert, D. Hentschel, Fraunhofer-Institut für Zerstörungsfreie Prüfverfahren (Germany)

shall be submitted directly to chair

6179-11, Session 2

Measurement of coating thickness using ultrasonic resonance spectroscopy

S. B. Palmer, Univ. of Warwick (United Kingdom)

A technique has been developed whereby the thickness and elastic modulus of a coating applied to a substrate can be calculated from measurement of the resonant bulk wave ultrasonic modes of the combined substrate and coating. The density of the coating and the material properties of the substrate are required for this method. We have investigated the difference between models that take account of material attenuation and simpler models that do not and have found that there is little difference in the predicted resonant frequencies of the system for modes that can be observed in the experimental data. We have applied the technique to explain the experimental measurements for a 100μm thick epoxy resin coating curing on a 1mm thick aluminium substrate using wideband radially polarised SH shear waves. In this dynamic system the elastic properties of the coating change and particular resonant modes not only shift but can disappear or appear in the experimental data. The model is used to explain this behaviour and show that the technique has potential for coating thickness measurement in other areas.

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6179-12, Session 2

Staircase ultrasonic array for enhanced scanning

K. Oliver, B. R. Tittmann, The Pennsylvania State Univ.

Industrial applications often limit the number of electrical wires to an ultrasonic array. This in turn limits the number of elements an array can excite and therefore the resolution and coverage on the target. Here results are reported for a 4 wire array which can excite and receive via 12 elements. This is accomplished by means of a "stair-case" design. Three sets of 4 elements are ganged together so that they scan simultaneously different parts of a target. The three sets of elements are off-set in space and therefore in time. A multiplexer gates out the relevant waveforms and combines them to provide three simultaneously scanned beams. The target in this case is a thick plate of metal alloy to be characterized for flaws such as corrosion blisters, surface cracks and dimensional changes, such as warping. Described are the results of the design approach with the aid of two 2-D simulation programs (Field-II and Wave Pro 2000) which show the three beams and their side lobes as they scans through 90 degree sectors on 3 adjacent parts of the surface of the target. These results are compared to experimental scans with a 4 element array to image drill holes in a block of Plexiglas with good agreement.

6179-13, Session 2

Development of Z-shaped patch-type magnetostrictive torsional transducer

C. I. Park, S. H. Cho, Y. Y. Kim, Seoul National Univ. (South Korea)

Guided-waves have been widely used for the long-range non-destructive damage detection of cylindrical waveguides such as pipes and tubes. Since the torsional wave mode is the most attractive because of their non-dispersive characteristic, the magnetostrictive transducer generating and measuring this wave mode will be mainly considered in this work. The magnetostrictive effect represents the coupling phenomena between magnetic field and mechanical deformation of magnetostrictive materials such as nickel. Since existing transducers require circumferential pre-magnetization of the nickel patch before actual experimentation, they are not suitable for long-term on-line monitoring because of the possibility of spoiled magnetization. Thus we have recently developed a new transducer that does not require pre-magnetization. Specifically, a transducer using slender rectangular nickel patches that are bonded 45 degrees to the pipe/tube axial direction is developed. In this work, the main concern is to increase substantially the output of the transducer and to improve its signal-to-noise ratio. To achieve this objective, the use of yokes was considered to concentrate the magnetic flux density at the slender rectangular patch. After carrying out design optimization and considering some practical design aspects, a specially-shaped yoke configuration has been designed. If the yokes are attached at both ends of the rectangular patch, the patch looks like an alphabet character Z. Thus the newly-developed patch will be called the Z-shaped patch (or Z patch). Several sets of experiments were conducted to check the transduction efficiency of the proposed transducer configuration. When the Z-shaped patches were employed in actual experiments, the magnitude of the measured wave signal was 13 times larger than that by the yokeless patch-type transducer. Other experimental findings are also reported in this work.

6179-14, Session 2

Low-attenuation waveguides for leaky surface waves

K. L. Joseph, B. R. Tittmann, The Pennsylvania State Univ.

This report is on the study of elastic wave propagation in multi-layer systems. In the experiments, the elastic wave is launched from the top of the first layer (a solid), propagates through a second layer (a fluid), into a third layer (a solid); and then it propagates down the length of the third layer to an impedance boundary. A large portion of the elastic wave energy then reflects back through the layers to the top of the first layer and is received by a sensor. The motivation for this study is the furthering of understanding of selective wave propagation over long distances. The applications range from seismic prospecting for an oil bearing stratum through a water table, to detecting a crack through a double-wall heat exchanger and to determining the position of the top of an industrial lead screw separated with pressurized high temperature water from another wall. It is well known that a surface wave on a liquid/solid interface radiates acoustic energy into the liquid and is therefore rapidly attenuated. We have been able to show by experiments and calculations that the proximity of another surface (layer 1 to layer 3 and layer 3 to layer 1) sustains the surface wave through long distances for layers of both plates and concentric tubes. In addition, even when the surface wave is reflected from a distant edge, the returning wave is sustained in the multi-layer system and can be easily detected. The details of the experiments are discussed and analysed in this report. This is apparently one of the first observations of leaky surface waves travelling over large distances, in this case over a thousand wavelengths. The effect is modelled on the basis of a cooperative phenomenon between two interfaces separated by a water layer. The result represents an interesting facet of the wave propagation of acoustic surface waves and opens the door to many applications.

6179-15, Session 2

Guided-wave transduction in nonferromagnetic plates using a circular magnetostrictive patch

S. H. Cho, J. S. Lee, Y. Y. Kim, Seoul National Univ. (South Korea)

Guided-waves have been widely used for the long-range non-destructive damage detection of cylindrical waveguides such as pipes and tubes. Since the torsional wave mode is the most attractive because of their non-dispersive characteristic, the magnetostrictive transducer generating and measuring this wave mode will be mainly considered in this work. The magnetostrictive effect represents the coupling phenomena between magnetic field and mechanical deformation of magnetostrictive materials such as nickel. Since existing transducers require circumferential pre-magnetization of the nickel patch before actual experimentation, they are not suitable for long-term on-line monitoring because of the possibility of spoiled magnetization. Thus we have recently developed a new transducer that does not require pre-magnetization. Specifically, a transducer using slender rectangular nickel patches that are bonded 45 degrees to the pipe/tube axial direction is developed. In this work, the main concern is to increase substantially the output of the transducer and to improve its signal-to-noise ratio. To achieve this objective, the use of yokes was considered to concentrate the magnetic flux density at the slender rectangular patch. After carrying out design optimization and considering some practical design aspects, a specially-shaped yoke configuration has been designed. If the yokes are attached at both ends of the rectangular patch, the patch looks like an alphabet character Z. Thus the newly-developed patch will be called the Z-shaped patch (or Z patch). Several sets of experiments were conducted to check the transduction efficiency of the proposed transducer configuration. When the Z-shaped patches were employed in actual experiments, the magnitude of the measured wave signal was 13 times larger than that by the yokeless patch-type transducer. Other experimental findings are also reported in this work.

6179-16, Session 2

Evaluation of debonding progress in composite bonded structures by ultrasonic wave sensing with fiber Bragg grating sensors

Y. Okabe, J. Kuwahara, N. Takeda, The Univ. of Tokyo (Japan); T. Ogisu, Fuji Heavy Industries, Ltd. (Japan); S. Kojima, S. Komatsuzaki, Hitachi Cable, Ltd. (Japan)

The authors are constructing a damage detection system using ultrasonic waves. In this system, a piezo-ceramic actuator generates ultrasonic waves in a carbon fiber reinforced plastic (CFRP) laminate. After the waves propagate in the laminate, transmitted waves are received by a fiber Bragg grating (FBG) sensor attached on the laminate using a newly developed high-speed optical wavelength interrogation system.

Hence, short FBG sensors were applied to the detection of Lamb waves propagated in CFRP cross-ply laminates. The piezo-actuator put on the laminate excited three-cycle sine waves of 300kHz with Hamming window repeatedly. The waveforms obtained by the FBG showed that S0 and A0 modes could be detected appropriately. Then, artificial delamination was made in the laminate in the 0/90 interface of the laminate. When the Lamb waves passed through the delamination, the amplitude decreased and a new wave mode appeared. These phenomena could be well simulated using a finite element method. From the changes in the amplitude ratio and the arrival time of the new mode depending on the delamination length, it was found that this system has a potential to evaluate the interlaminar delamination length quantitatively.

Then, small-diameter FBG sensors, whose cladding diameter is about 1/3 of common optical fibers, were embedded in an adhesive layer of a double-lap type coupon specimen consisting of CFRP quasi-isotropic laminates, and the ultrasonic wave was propagated through the debonded region. After that, the wavelet transform was applied to the received waveforms and the results showed clear difference depending on the debonding length. This is because the debonding progress in the bonded structure causes the changes in the frequency and the arrival times of many modes excited in the complicated bonded structures.

Hence this system was applied to the skin-stringer structural element of airplanes made of CFRP laminates in order to detect the debonding between the skin and

the stringer. In this experiment, elastic waves are generated from the piezo actuators on the surface of the skin and are received by the FBG sensors embedded in the adhesive layer between the skin and the stringer. As a result, depending on the size of the debonding, the shapes of the received waves were changed. Thus, the wavelet transform was also applied to the received waves, and a new damage index was proposed, which could be obtained from the difference in the distribution of the wavelet transform coefficient. As a result, the damage index increased with an increase in the debonded area. Now, the authors are attempting to apply broadband ultrasonic waves to obtain more information for the increase in the accuracy of the debonding estimation. Simultaneously, the visualization software for the debonding detection in the CFRP skin-stringer structure is being developed.

6179-17, Session 2

Stiffness monitoring and health monitoring of civil concrete structure by using built-in piezoelectric transducers

H. Gu, G. Song, Univ. of Houston

It is important to conduct stiffness monitoring of the concrete during the casting process. Piezoelectric-based monitoring method provides a new approach to experimentally conduct stiffness monitoring for concrete structure during the casting process. Distributed piezoelectric transducers were embedded into the concrete as actuator and sensors before casting. Sweep sine, sinusoidal signal and sinc signal were used as propagation waves separately. Two concrete specimens have been tested as testing objects. From the experimental results, the amplitude of the sensor signal decreased greatly in the first 28 days and remained stable after 28 days which matches the theoretical curve of the stiffness change. This shows the piezoelectric sensor signal can reveal the change in the stiffness of concrete. An index is formed from sensor signal to represent the stiffness change inside the concrete. Heath monitoring of concrete specimens was conducted after the stiffness of concrete remained stable. A damage index was formed to track the growth of cracks happened inside the concrete. The proposed piezoelectric-based method has the potential to monitor the stiffness change during the casting process for concrete civil structure and conduct health monitoring after the concrete is casting.

6179-18, Session 3

Embedded PZT reliability test on CFRP specimens for active SHM under electrical fatigue loading

C. A. Paget, Airbus UK (United Kingdom); K. Levin, Swedish Defence Research Agency (Sweden); S. Mall, Air Force Research Lab.

The electrical fatigue performance of embedded piezoceramic transducers in composites, being used as Lamb wave generators, was investigated experimentally. Tests were conducted with two types of transducers. The first type was smaller in size than the second type. The second type was a commercially available lead zirconate titanate (PZT) transducer. The transducers were electrically fatigued for one billion cycles using a pulse-based electric loading of various electric field levels. The investigation demonstrated that the electrical fatigue loading of embedded transducers in composites did not reduce the electrical functioning/performance limits of the transducers. On the contrary, after few millions of electrical loading cycles, the electrical functioning limits were improved.

6179-19, Session 3

Nanoscale deformation measurements to improve reliability assessment of sensors and MEMS

B. Michel, Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration (Germany); J. Keller, H. Walter, AMIC GmbH

Micromachined micro sensors for gas or flow detection based on physical behaviour of a special layer of a membrane have to fulfil high quality and reliability requirements especially in safety or security applications. Up to now, most of the studies of this kind of devices have been focused on power consumption and fast response achieved by the implementation of the device over dielectric membranes, but often mechanical issues related to reliability of these structures have been neglected. In this sense, the study and characterization of the stress distribution on the membranes after fabrication and during their operative life is required.

Thin films used in micromachined structures exhibit residual mechanical stress strongly dependent on the layer composition and the deposition process parameters. Often, a deposition of a multilayer is required, and this adds factors like abrupt transitions in thermal, elastic and plastic mismatch across the interfaces that have a direct effect on the resultant stress. Moreover, in operating conditions, a thermal stress originated due to the difference in the thermal expansion coefficient (CTE) of the membrane materials adds to the residual stress of the membrane. The resultant stresses can induce consequences such as excessive deformation, fracture, delamination and microstructural changes in the material that can lead to the breaking of the structure during the fabrication stage or affect the behaviour of the final device.

In the present work, the 2D deformation of a gas and a flow sensor membrane under different thermo-mechanical load states will be analysed by means of the digital image correlation techniques based on scanning probe microscopy (SPM) data. With this technique which is introduced as the nanoDAC method (nano Deformation Analysis by Correlation) deformation fields can be determined with nanometer-accuracy.

6179-20, Session 3

Evaluation and improvement in sensor performance and durability for structural health monitoring systems

J. L. Blackshire, A. T. Cooney, Air Force Research Lab.

For aerospace applications, the successful transition and use of integrated structural health monitoring systems will require durable sensors that can perform in their intended environment for many years. For legacy aircraft the primary means of implementing a sensor system will be through surface mounting or bonding of the sensors to the structure. Previous work has shown that the performance of surface-bonded piezo sensors can degrade due to environmental effects such as vibrations, temperature fluctuations, and substrate flexure motions. This performance degradation included sensor cracking, disbonding, and general loss of efficiency over time. In this activity, the bond and piezo material characteristics of a typical surface-bonded piezo sensor system were studied to understand and improve the long-term durability and survivability of the sensor system. Analytic and computational models were developed and used to understand stress-strain relationships for the bonded sensor system, with a special emphasis being place on coefficient of thermal expansion issues. Accelerated environmental testing was accomplished for several different bonded piezo sensor systems, where a displacement-field imaging technique was used to understand the piezo sensor performance. Future activities will focus on identifying the optimal bond conditions and piezo material type, with the ultimate goal of improving the robustness of health monitoring systems through improved sensor system design and packaging.

6179-21, Session 3

Full implementations of structural health monitoring systems for long-span bridges and large-span domes

H. Li, Harbin Institute of Technology (China)

In this paper, full implementations of structural health monitoring systems for long-span bridges and large-span domes are introduced. The frameworks of the health monitoring systems are introduced. The types and locations of sensors are also presented. The data acquisition system, including scheme of data acquisition system, strategies of collecting data, instrument and software used in the data acquisition system, is described. The data transmitting system, data management system and warning system are also designed. Based on the data collected by the structural health monitoring systems, response and dynamic properties of the structures, and the loads are statistically analyzed. Finite element (FE) model is updated based on the measured data by structural health monitoring. Finally, the safety of the structures is evaluated by utilizing updated FE model.

6179-22, Session 3

In situ monitoring of the integrity of bonded repair patches on civil inrastructures

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Bonded repair is becoming a preferred technique for repairing localized damage in aerospace and civil infrastructures such as aircraft and bridges. These repairs provide an efficient method for restoring the ultimate load capability of the structure. They also offer several advantages over bolted repairs, including minimal changes to the structure, weight savings, reduced cost, and formability to complex shapes. More importantly, bonded repair patches can stop or significantly retard fatigue crack growth in the original structure, while avoiding new fatigue cracks caused by the addition of fastener holes to install traditional repairs.

However, the effectiveness of a bonded repair depends heavily upon the integrity of the bonding interface between the repair patch and the host structure. Cur-

rently there are no inspection methods for determining the initial "quality" of the bond or for assessing the long-term durability of the repair. In addition to potential bondline degradation, flaws and damage, such as a disbond, can have a detrimental effect on the integrity of the bond strength. Disbonds can arise from fatigue loading, impact events, or improper surface preparation during installation. In addition, surveillance of repaired cracks - to ascertain growth beyond allowable limits - may be necessary. Therefore, inspection of bonded repair installation is an essential part of regular structural maintenance. The rapid and uncomplicated application of such inspections is essential to minimizing the time and labor associated with deployment and data interpretation.

The use of in-situ sensors can produce smart structures that allow for condition-based maintenance and more frequent inspections. In this presentation, a novel method for in-situ monitoring of the integrity of bonded repair patches for application to civil infrastructures is presented. The method has been adapted from an existing SMART Patch system for aerospace structures that utilizes a network of miniature piezoelectric sensors to query the health of a chosen hot-spot area.

Issues such as sensor design, integration, data collection and data analysis and interpretation will be presented. Quantitative results from tests conducted on representative coupon specimens for monitoring of disbonds and crack propagation will also be presented along with comparisons with existing techniques used currently for damage detection in bonded repair.

6179-23, Session 4

Research and practice of intelligent sensing technologies in civil structural health monitoring in the mainland of China

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Intelligent sensing technologies have developed rapidly recent years, which meet the requirement of structural health monitoring. A number of types of intelligent sensing technologies have been developed in the mainland of China, such as optical fiber sensing technology, piezoelectric sensing technology, self-sensing smart materials, wireless sensors and sensor networks, CCD, GPS and so on. In this paper, various optical fiber sensors are introduced, including optical fiber sensors, six kinds of optical fiber Bragg grating (OFBG)- based sensors, fiber reinforced bars embedded with OFBG sensors (FRP-OFBG), OFBG-based smart cables, OFBG-based weighbridge, PZT- and PVDF-based strain gauge and crack meter, fatigue meters, shape memory alloy-based displacement transducer, self-sensing cement-based strain gauge, wireless accelerometers and sensor networks, wireless strain sensors and sensor networks, CCD technology, and GPS. The performance of various sensors mentioned above is also experimentally investigated, in particular sensing property, durability, fatigue and corrosion resistant performance. Additionally, applications of the sensors have also been carried out in the mainland of China. The full implementation of sensors in health monitoring systems for offshore platforms, long-span bridges, large-span domes, tall buildings and so on are also introduced in this paper. Finally, the results of data interpretation and diagnostics civil structural health monitoring based on the implemented health monitoring systems are presented.

6179-24, Session 4

Detection of acoustic emission wave by using optical fiber sensor during single-pulse discharge

Y. Akematsu, K. Kageyama, N. Mohri, H. Murayama, The Univ. of Tokyo (Japan); M. Matsuo, Canon Inc. (Japan)

There are great demand for different kinds of Acoustic Emission (AE) measurement systems for extensive area of AE applications, where it is preferable that various types of AE sensor in accordance with the applications. However, almost all the AE sensors in practical use now are piezoelectric. While the piezoelectric sensor has various advantages, it is difficult to AE monitoring due to an indication of electrical noise. In order to overcome some problems of AE monitoring system, optical fiber sensor has been developed. AE monitoring system using optical fiber sensor is compact, light weight and free of electromagnetic hazard. In our laboratory, optical fiber sensor has been developed based on the Doppler Effect. The optical fiber sensor can be detected the displacement velocity in wideband from 0.1Hz to several MHz. The displacement velocity was able to be measured by bonding manufactured optical fiber sensor on a surface of a specimen. The displacement can be caluculated by integrating the signal detected by the optical fiber sensor, because of the optical fiber sensor is able to detect AE in wideband. It paid attention to the single pulse discharge phenomenon which generate wideband AE with an electrical noise. The single pulse discharge circuit was made so that the single pulse discharge duration might become 1μs. Moreover, in order to be happened single pulse discharge, charging time was controlled several 10ms. Single pulse discharge was happened to the center of a wide aluminum lamina so that the influence of the reflection wave can be ignored.

This paper describes some experimental results on a fundamental phenomenon of the single pulse discharge. The single pulse discharge phenomenon was measured by using the optical fiber sensor, piezoelectric sensor and current transducer. In order to investigate the generation factor and propagation characteristic of AE by single pulse discharge in oil, the voltage across the gap, the discharge current and the displacement were measured. Detected the signals using the optical fiber sensor and piezoelectric sensor have been compared with each other. As the results, optical fiber sensor was more resist than piezoelectric sensor in an electromagnetic noise. It is likely that the optical fiber sensor was more useful than piezoelectric sensor for AE detection with electromagnetic field. In order to investigate the relationships between the single pulse discharge phenomena and the detected AE signals, numerical analysis by using finite element method (FEM) was adapted. The numerical analysis result using the FEM and the experiment result along with the single pulse discharge was compared. As the result, it was estimated that the generation factor of the AE wave was the 1μs duration force. The signal detected by the optical fiber sensor has a good agreement with the signal from the FEM one. It is found that optical fiber sensor can detect the displacement with wide band. Moreover, it was considered that frequency response of the optical fiber sensor is approximately flat. The optical fiber sensor was effective in analysis of AE source.

6179-25, Session 4

Efficient large-scale multiplexing of fiber Bragg grating and fiber Fabry-Perot sensors for structural health monitoring applications

G. A. Cranch, G. M. H. Flockhart, Sachs Freeman Associates, Inc.; C. K. Kirkendall, Naval Research Lab.

Fiber Bragg gratings have been demonstrated as a versatile sensor for structural health monitoring. We present an efficient and cost effective multiplexing method for fiber Bragg grating and fiber Fabry-Perot sensors based on a broadband mode-locked fiber laser source and interferometric interrogation. The broadband, pulsed laser source permits time and wavelength division multiplexing to be employed to achieve very high sensor counts. Interferometric interrogation also permits high strain resolutions over large frequency ranges to be achieved. The proposed system has the capability to interrogate several hundred fiber Bragg gratings or fiber Fabry-Perot sensors on a single fiber, whilst achieving sub-microstrain resolution over bandwidths greater than 100 kHz. Strain resolutions of 30ne/Hz1/2 and 2 ne/Hz1/2 are demonstrated with the fiber Bragg grating and fiber Fabry-Perot sensor respectively. The fiber Fabry-Perot sensor provides an increase in the strain resolution over the fiber Bragg grating sensor of greater than a factor of 10. The fiber Bragg gratings are low reflectivity and could be fabricated during the fiber draw process providing a cost effective method for array fabrication. This system would find applications in several health monitoring applications where large sensor counts are necessary, in particular acoustic emission.

6179-26, Session 4

Application of distributed long-gauge fiber optic sensors in structural assessment for reinforced concrete beams

S. Li, Z. Wu, Ibaraki Univ. (Japan)

In our resent study, a novel packaged long-gage fiber optic sensor for practical adaptation in civil structural health monitoring has been developed and verified to have the ability to obtain effective macro-strain distributions. This paper discusses the application of the proposed sensor in damage identification for reinforced concrete structures. A RC beam of 2m length with distributed long-gage FBG sensors are utilized for experimental investigations, in which progressing cracking is introduced in different loading steps and respective measurements under both static and dynamic tests are obtained. Damage detection is performed by relating the changes of various characteristics extracted from macro-strain distributions measured by long-gage sensors such as static stiffness, natural frequency, modal macro-strain vector and their derived damage indexes to the level of crack damage introduced in the beam. The capability and effectiveness of diverse characteristics for damage identification are compared to provide a basis on structural assessment for RC beams.

6179-27, Session 4

Influencing parameters analysis of strain transfer in optic fiber Bragg grating sensors

G. Zhou, H. Li, L. Ren, D. Li, Dalian Univ. of Technology (China)

Optic fiber Bragg grating sensor is a new type of sensor. It is playing an important role in structural healthy monitor. When the optic fiber Bragg grating sensor is embedded in the structure or adhered to the structure, a strain transfer coefficient exists because that there is an interlayer between structure and sensor. This paper educes important factors that effect the strain transfer on the base of exist theory. The parameters are the length of the sensor, the thickness, Young's modulus and Poisson's ratio of interlayer. At the same time, the paper analyzes different influence factors to strain transfer rate, which provides a theoretical basis for next researches and designs.

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