Technical Abstract Summaries

SPIE Smart Structures/NDE

Conferences and Courses: 7–11 March 2010
Exhibition: 9–10 March 2010

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Conf. 7642: Electroactive Polymer Actuators and Devices (EAPAD) XII

Monday-Thursday 8-11 March 2010

Part of Proceedings of SPIE Vol. 7642 Electroactive Polymer Actuators and Devices (EAPAD) 2010

7642-01, Session 1

Biomimetics: lessons from nature

B. Bhushan, The Ohio State Univ. (United States)

Nature has developed materials, objects, and processes which function from the macroscale to the nanoscale. These have gone through evolution over 3.8 billion years. The emerging field of biomimetics allows one to mimic biology or nature to develop nanomaterials, nanodevices, and processes1. Properties of biological materials and surfaces result from a complex interplay between surface morphology and physical and chemical properties. Hierarchical structures with dimensions of features ranging from macroscale to the nanoscale are extremely common in nature to provide properties of interest. Molecular scale devices, superhydrophobicity, self-cleaning, drag reduction in fluid flow, energy conversion and conservation, high adhesion, reversible adhesion, aerodynamic lift, materials and fibers with high mechanical strength, biological self-assembly, anti-reflection, structural coloration, thermal insulation, self-healing, and sensory aid mechanisms are some of the examples found in nature which are of commercial interest. This talk will provide a broad overview of various objects and processes of interest found in nature and applications under development or available in the marketplace. The recent research on superhydrophobicity, self-cleaning, low adhesion/stiction, and drag reduction in fluid flow2,3 will be highlighted.

1Bhushan, B., “Biomimetics: Lessons from Nature -An Overview,” Phil Trans. R. Soc. A (in press).

2Nosonovsky, M. and Bhushan, B., Multiscale Dissipative Mechanisms and Hierarchical Surfaces: Friction, Superhydrophobicity, and Biomimetics, Springer, Heidelberg, Germany, 2008.

3Bhushan, B. Jung, Y. C. and Koch, K., “Micro-, Nano-, and Hierarchical Structures for Superhydrophobicity, Self-Cleaning and Low Adhesion”, Phil. Trans. R. Soc. A (in press).

7642-02, Session 1

Ionic liquid-based ionic polymer transducers: a review

D. J. Leo, Virginia Polytechnic Institute and State Univ. (United States); B. J. Akle, Lebanese American Univ. (Lebanon); A. J. Duncan, Virginia Polytechnic Institute and State Univ. (United States)

Ionic polymer transducers (IPT) are large strain low voltage Electro-Active Polymer (EAP) actuator. These ionic transducers made of an ionic polymer membrane in which the cation is free to move while the anion is covalently attached to the polymer backbone. The membrane is sandwiched between two high surface area electrodes toward which the cations migrate upon the application of an electric field. The redistribution of ions is agreed upon for being the reason for the electromechanical actuation. Traditionally IPTs requires water to dissolve and mobilize the free cations inside the ionic polymer membrane. Although some researchers attempted to package the water hydrated IPT and use it in air, the use of these actuators remained limited to underwater applications. To overcome this issue, Bennett and Leo (200x) hydrated the IPTs with vapor free ionic liquids. These liquids are special types of salts that are molten at room temperature and exhibit immeasurable vapor pressure. When saturated with ionic liquids, IPTs perform millions of cycles in air without significant degradation in performance. In this paper we will review the manufacturing techniques, the actuation performance, the mathematical modeling efforts, and the reliability of these dry Electroactive actuators. A special manufacturing technique denoted the Direct Assembly Process (DAP) is developed to manufacture these dry actuators. Several variants of this manufacturing technique are presented and the performance of the resulting actuators is compared. Actuation performance is characterized in both bending mode and in extensional mode. The free displacement and the blocked force are measured for several types of applied potential such as the step input, sine wave, and square wave. An important feature of the DAP manufacturing technique is the ability to control and vary the architecture of the electrode in an IPT. The electrode architecture is proved to be critical to the performance of the IPT, hence by increasing its thickness the performance of the IPT will increase almost proportionally. Ruthenium Dioxide, Platinum, and Single Walled Carbon Nanotubes are among the several materials studied in the electrodes of an IPT. Alos presented in this paper is a model depicting the electrode as an active area, while the middle membrane of an IPT as a passive area. The active areas model is experimentally verified in bending and extension modes. Furthermore, presented in this paper are the morphological studies performed by Bennett and Leo and compared to the experimental data of the electromechanical characterization of the ionic liquid based IPTs. In this study the authors varied the types and concentration of ionic liquids, and they concluded that the ionic liquids are disrupting the morphology of the ionic polymer. Finally a reliability study of the dry actuators that demonstrates good performance up to 1 million is presented. This reliability study showed that the limitation is not due to the ionic liquid but the adherence of the electrodes to the membrane.

7642-03, Session 1

Carbon nanotube yarn as a microscale rotational actuator

J. Foroughi, Univ. of Wollongong (Australia); T. Mirfakhrai, The Univ. of British Columbia (Canada); R. H. Baughman, S. Fang, M. E. Kozlov, The Univ. of Texas at Dallas (United States); J. D. W. Madden, The Univ. of British Columbia (Canada); G. M. Spinks, G. G. Wallace, Univ. of Wollongong (Australia)

Actuator materials capable of producing a rotational motion are rare and, yet, rotary systems are extensively utilized in mechanical systems like electric motors, pumps, turbines and compressors. Rotating elements of such machines can be rather complex and, therefore, difficult to miniaturize. Rotating action at the microscale, or even nanoscale, would benefit from the direct generation of torsion from an actuator material. We have discovered that the electrochemical charging of helically wound multiwall carbon nanotubes in the form of a twisted yarn generates such rotational action. Large scale rotations are produced from small voltage stimuli. The rotation angles are orders of magnitude larger than piezoelectric or shape memory alloy torsional actuators. The torsional strain, torque, speed and lifetime have been evaluated under various electrochemical conditions to provide insight into the actuation mechanism and performance. Finally, the rotating motion has been coupled to a mixer for use in a prototype microfluidic system.

7642-04, Session 2

Refreshable Braille displays using electroactive polymer (EAP) actuators

Y. Bar-Cohen, Jet Propulsion Lab. (United States)

The ability to read Braille text using a refreshable display helps vision impaired persons benefit from the growing advances in computer technology. The development of such displays in a full screen form is great challenge due to the need to pack many actuators in a small area without interferences. In recent years, various displays using actuators such as piezoelectric stacks have become available in commercial form but most of them are limited to one line. In recent years, researchers in the field of electroactive polymers (EAP) investigated methods of using these materials to form full screen displays. On the broader level efforts are sought to develop haptic and tactile interfaces/displays as tools for interaction with and/or thru computers. The applications include teleoperators and simulators, computer interfaces and video

games (e.g., joysticks and Wii), robotics, tactile displays, surgical force-feedback devices, and many others. In order to take advantage of the unique possibilities that EAP can provide this subject is was chosen for highlight as a special session in the 2010 EAPAD Conference and abstracts as well as demos for the EAP-in-Action Session will be sought. This manuscript reviews the state of the art in EAP based refreshable Braille displays.

7642-05, Session 2

EAP actuators aid the quest for the 'Holy Braille' of tactile displays

N. H. Runyan, National Braille Press (United States) and Personal Data Systems, Inc. (United States); D. B. Blazie, National Braille Press (United States) and Blazie Engineering, Inc. (United States)

The Boston-based National Braille Press has recently established a Center for Braille Innovation (CBI), whose mission is to research and develop affordable braille literacy products. The primary focus has been to facilitate the development of dramatically lower cost electronic braille display devices, and the much-sought-after "Holy Braille" of a full-page braille display.

In the spirit of that mission, we discuss the needs and requirements for new tactile display devices to help improve the extremely low literacy rate of blind students and to reduce the high unemployment among non-braille readers who are visually impaired.

The report also discusses the needs and requirements of tactile graphic image displays, optical-tactile print converters for reading systems, "full" vision substitution arrays for "seeing-by-feel", tactile virtual reality systems, and compact tactile displays for watches, calculators, cell phones, and other small devices.

The NBP specs include braille dot dimensions, spacing, displacement, lifting force, and response time requirements. In addition to summarizing the technical requirements and specifications for braille and other tactile displays, the NBP web site and other sources of tactile display specifications will be referenced.

We discuss human factors issues, such as why multiplexing with only a single braille character display is not acceptable for most applications.

Several of the common and repeated pitfalls and assumptions that have led many previous tactile display developments astray are reviewed, in hopes that knowledge of these pitfalls will help developers avoid similar, misguided approaches. Our report reviews some of the major design limitations that caused many braille display developments to fail.

The CBI's prior art listing of tactile display projects is briefly reviewed and referenced, including some of the most notable past and current projects utilizing solenoids, wax expansion, bimetallic expansion, shape memory alloys, and both moving elastomer and plastic belt loop displays.

Associated with our presentation, there will be a significant exhibit of a wide variety of braille and tactile display devices, which should offer attendees a rare opportunity to literally get a hands-on feel for tactile display technologies and see what's under their hoods.

Finally, we summarize the results of our investigations into tactile display prior and current art, and list what appear to be the remaining challenges to developing practical tactile displays employing EAP actuator materials.

7642-06, Session 2

PVDF actuators for Braille displays

T. Levard, P. J. Diglio, C. D. Rahn, L. J. Gorny, Q. M. Zhang, The Pennsylvania State Univ. (United States)

Multi-line refreshable Braille displays have generated research interest because they allow blind people to interface with computers. This paper addresses the challenge of producing miniature and reliable actuators that generate the required 0.5 mm displacement and 100 mN force in a low profile and 2 mm diameter form factor. PVDF films were stretched in the machine direction to a thickness of 6 μm and formed into roll actuators using an automated manufacturing process. The film was first wrapped once around a 4 sided paddle along the machine direction. Individually controlled vacuum on each side of the paddle held the film along the edges. Conductive polymer was then sprayed on the PVDF Perpendicular to the Machine Direction (PMD) to act as a ground electrode. A second film layer was wound on and sprayed to provide the positive electrode. The double-layer electroded film was cut along the edges of the paddle using a knife. A heated, rotating mandrel contacted the film and rolled up the actuator in the PMD to produce a multi-layer tubular cylinder actuator (Length 5cm; ID 1.5mm; OD 2mm). The actuators were experimentally tested for displacement and blocking force.

7642-07, Session 2

The integration of novel EAP-based Braille cells for use in a refreshable tactile display

N. H. Di Spigna, P. Chakraborti, D. A. Winick, P. Yang, T. K. Ghosh, P. D. Franzon, North Carolina State Univ. (United States)

The continued development of the hydraulic and latching Braille cell is presented. The effects that the material properties of the sealing membrane and the shape of the lithographically defined bimorph electrodes have on the polyvinylidene fluoride (PVDF) bimorph tip displacement and the hydraulic operation of the cell have been analyzed. A custom automated characterization program has been developed to enable rapid and systematic data extraction of the bimorph actuation. Testing of a prototype cell, along with the challenges involved in its component interactions and fabrication, are discussed. In addition, further development of the dielectric elastomer fiber actuator has been investigated. The insertion of a spring core under compression inside the prestrained electroactive polymer (EAP) tube has been added to enhance the Braille cell properties. The effect that this inner spring has on the axial strain and blocking force of a prototype cell has been evaluated. The application of the two novel cell designs in meeting the requirements of a full-page, portable, refreshable Braille display is discussed.

7642-08, Session 2

Compact electroactive polymer actuators suitable for Braille display

L. J. Gorny, M. Lin, S. Liu, Q. M. Zhang, The Pennsylvania State Univ. (United States)

The small strain level and brittle nature of piezoceramic actuators used in the present commercial Braille display make it a challenge to develop full page and graphic Braille display with compact size and affordable price. On the other hand, recently developed electrostrictive P(VDF-TrFE-CFE) terpolymer with the large strain (~5%), fast actuation speed, and relatively high elastic modulus possesses great potential for compact Braille actuators suitable for full page and graphic Braille displays. This talk presents recent work in developing electrostrictive PVDF terpolymer based Braille actuators which exhibit tip displacement of 1 mm and force level more than 0.5 N with very compact size. In order to further improve the Braille actuator performance, a new class of terpolymer blends was developed recently which shows more than twice the elastic energy density of the original electrostrictive terpolymer. To match the requirement of 200 volts operation voltage, used in the commercial Braille display with piezoceramic bending actuators, a terpolymer film roll-to-roll zone drawing machine was designed and developed. Making use of this machine, the electrostrictive polymer films of 2 um thick has been produced with high quality. As a result, the newly developed electrostrictive Braille actuators can be operated under 200 volts, meeting the commercial Braille display requirement.

7642-09, Session 4

Bistable electroactive polymers (BSEP)

Q. Pei, Univ. of California, Los Angeles (United States)

Bistable electroactive polymers (BSEP)

Zhibin Yu, Paul Brochu, Xiaofan Niu, Wei Yuan, Huafeng Li, Qibing Pei

Department of Materials Science and Engineering, University of California, Los Angeles, CA 90095, USA

The ability to produce reversible, large-strain, bistable actuation has been the Holy Grail in the pursuit of smart materials and structures. Conducting polymers are bistable, but the achievable strain is small. Large deformations have been achieved in dielectrical elastomers at the sacrifice of mechanical strength. The gel or gel-like soft polymers generally have elastic moduli around or less than 10 MPa. The deformed polymer relaxes to its original shape once the applied electric field is removed. We report new, bistable electroactive polymers (BSEP) that are capable of electrically actuated strains greater than 200%. We will discuss the various applications enabled by the BSEP including Braille displays that can quickly refresh and maintain the displayed contents without a bias voltage.

7642-10, Session 4

Vibrotactile display for mobile applications based on dielectric elastomer stack actuators

M. Matysek, P. Lotz, K. Flittner, H. F. Schlaak, Technische Univ. Darmstadt (Germany)

Dielectric elastomer stack actuators (DESA) offer the possibility to build actuator arrays at very high density. Depending on the film thickness the actuator's driving voltage can be defined. We recently published details of or multilayer technology to reduce the driving voltage below 500V. In this paper we present the development of a vibrotactile display based on this technology which is used to present several operating conditions of a machine as haptic information to a human finger. As an example the design of a MP3-player interface is introduced. To build up an intuitive and user friendly interface several aspects of human haptic perception have to be considered. Using the results of preliminary user tests the interface is designed and an appropriate actuator layout has been derived. The control of the actuators is important because there are many possibilities to present different information with a single actuator, e.g. by encoding the information in frequency, amplitude or pulses. The realized system allows an almost free configuration of the information encoding.

A built up demonstrator is used to investigate the concept of our display by further user tests. The high recognition rate of more than 90% validates the concept.

Finally the energy consumption of the device is determined. The required real power is less than 0.3mW while the reactive power is almost 100 times higher. Voltage and current of the actuator are 89.5° out of phase, thus, the actuator represents a nearly purely reactive load. Actuator design parameters affecting the power consumption are determined.

7642-11, Session 4

Hydrostatically coupled dielectric elastomer actuators for tactile displays and cutaneous stimulators

F. Carpi, G. Frediani, S. Tarantino, D. De Rossi, Univ. of Pisa (Italy)

Hydrostatic coupling has been recently reported as a means to improve versatility and safety of dielectric elastomer (DE) actuators. Hydrostatically coupled DE actuators rely on an incompressible fluid that mechanically couples a DE-based active part to a passive part interfaced to the load. In this paper, we present ongoing development of bubble-like versions of such transducers, made of silicone and oil. In particular, the paper describes both millimeter-scale arrays and centimeter-scale single units of actuators, currently being developed as soft, light, acoustically silent and cheap devices for two types of applications: tactile displays and cutaneous stimulators. In both cases, the most significant advantages of the proposed technology are represented by high versatility for design (due to the fluid based transmission mechanism), tailorable stiffness perceived by the user (obtained by adjusting the internal fluid pressure), and suitable electrical safety (enabled by both a passive interface with the user and the insulating internal fluid). Millimeter-scale prototypes have been fabricated so as to show a resonance frequency in the range 250-300 Hz, which represents the range wherein Pacinian cutaneous mechanoreceptors exhibit maximum sensitivity; this provides an optimum condition to eventually code tactile information dynamically, either in combination or as an alternative to static driving.

7642-12, Session 4

Flexible tactile sensor for robot fingertip

H. R. Choi, D. S. Kim, H. C. Nguyen, S. M. Jin, H. L. V. Nguyen, K. J. An, H. P. Vuong, J. C. Koo, J. Nam, Y. K. Lee, Sungkyunkwan Univ. (Korea, Republic of)

Tactile perception is one of the most important things for object manipulation in unknown environments. Currently, there are many kinds of tactile sensors which are developed using flexible PCB, PDMS etc. However they actually are not soft enough for 3D shaped applications like a robot hand because of their low flexibility. So in this paper we proposed the novel tactile sensor using dielectric elastomer which has high flexibility and strechability as a base material. Since the dielectric elastomer is conformable, it can be easily covered onto the curved robot fingertip surface. When pressure is applied to the sensor, the dielectric elastomer gets compressed, and the capacitance between top and bottom electrodes changes as they get closer. The developed tactile sensor consists of two conductive layers separated by a soft dielectric elastomer. We use flexible conductive silicone for each conductive layer. The inner conductive layer configured with multi-cells in order to detect both contact force and position and the outer conductive layer is regarded as a common ground to reduce the electrical noise coming from the environment. There are, in addition, two thin protection layers on top and bottom surface. In the proposed design, capacitive tactile sensor have been implemented using commercially available capacitance to digital converter integrated circuits(CDC), commonly used for example in cell phones. The CDC detects the variation of a capacitance and the measurements are sent to a microcontroller using inter integrated circuit(I2C) buses. A Microcontroller will send the tactile data to a host using a CAN bus.

7642-13, Session 4

Active polymers based high-resolution tactile display

A. Richter, G. Paschew, K. Arndt, Technische Univ. Dresden (Germany)

Here, we introduce a high-resolution tactile display (1). We present our artificial skin based on temperature sensitive "Smart Hydrogels" which displays both visual and palpable information. Each of the single actuators is controlled by a computer using an opto-electronical or a resistive interface and thereby generating a high resolution temperature field. The device containing an artificial skin consists of 4,225 individually controlled actuator pixels at a density of 300 actuators per cm^2. An actuator pixel changes the color from transparent to opaque, the altitude and the elasticity. Therefore the display is able to generate artificial impressions about contours, textures, profiles and the softness of a surface. The palpable impressions can be varied depending on the design of the device such as the layers surrounding the actuators or the actuator size, the resolution and the alignment. Due to its color change the polymer display provides also visual monochrome functionality. The artificial skin would allow physical-auditory interaction to improve the communication of visually impaired persons with electronic media. If the artificial skin is combined with image-based diagnostics then new features will be provided in teleoperations. The

palpable recognition of objects inside the body without the necessity to open it would improve diagnoses and allow preliminary simulation of surgical operations. Introducing tactile information within minimally invasive robotic surgery (MIRS) would combine the advantages of conventional open surgery, which is in particular the tactile recognition of the operation field, with that of the MIRS, e.g. for reduction of the operative trauma for the patient.

1) Richter, A.; Paschew, G. Adv. Mater. in press, DOI: 10.1002/adma.200802737.

7642-14, Session 4

EAP arrays of single-cell stretching devices for tissue engineering applications

S. Akbari, M. Niklaus, H. R. Shea, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Mechanical stimuli are critical for the development and maintenance of most tissues such as muscles, cartilage, bones and blood vessels. Commercially available cell stretching devices apply strain over areas greater than one cm^2, and can only measure the average response of large colonies of cells. We present here an array of 128 EAP micro-actuators which impose unidirectional strain on single cells, thus enabling for the first time, experiments on the cytomechanics of individual cells.

The 100x100 µm^2 dielectric elastomer actuators consist of 30 µm thick pre-stretched PDMS film (Sylgard 186) bonded onto a support frame in which 50 µm deep and 100 µm wide channels are patterned. Compliant gold electrodes are deposited by low-energy ion implantations, as this technique allows making electrodes that support large strain (175%) with minimal stiffening of the elastomer. 50 µm to 200 µm wide gold lines, orthogonal to the channels, are patterned under the membrane, and a continuous implanted electrode is deposited on the membrane. There is one actuator at the intersection of each channel and line, on which a cell can be attached.

Our current device with 128 actuators on a 4 cm^2 chip is driven by 4 independent control voltages, allowing different frequencies and amplitudes to be applied to sections of the array to permit simultaneous observation of cell behavior under various dynamic and static mechanical strains. We are currently calibrating strain versus the applied voltage, frequency and geometry. FEM simulations predict a 20% strain at 3.5 kV, easily covering biologically relevant levels.

7642-15, Session 4

Artificial muscle actuators for haptic displays: system design to match the dynamics and tactile sensitivity of the human fingerpad

S. J. Biggs, R. N. Hitchcock, Artificial Muscle, Inc. (United States)

Electroactive Polymer Artificial Muscles (EPAM) based on dielectric elastomers have the bandwidth and the energy density required to make haptic displays that are both responsive and compact. Recent work at Artificial Muscle has been directed toward the development of thin, high-fidelity haptic displays. The litmus test in many applications, for example touch screens, is the brief tactile “click” that confirms keypress. As such, the parameter of interest is the transient response of the system (actuator + display + fingertip). To design for a good click, it is useful to know the inertial, damping, and spring loads of these system components under transient conditions. Here we report on the dynamic properties of our dielectric elastomer actuators, as well as the dynamic properties of human fingerpads subjected to brief “click” transients. Effects of button-press force, transient amplitude and click duration are reported for a variety of users. Transient response for clicks, and steady-state response for longer effects such as music and games are compared.

7642-16, Session 5

Materials science on the nano-scale for improvements in actuation properties of dielectric elastomer actuators

G. Kofod, H. Stoyanov, M. Kollosche, S. Risse, H. Ragusch, D. N. McCarthy, Univ. Potsdam (Germany)

Three properties of the elastic medium in a dielectric elastomer actuator affect the actuation properties directly: dielectric constant, electric breakdown strength, and mechanical stiffness. The dielectric constant of a given elastomer can be improved by mixing it with other components with a higher dielectric constant, which can be classified as insulating or conducting. Insulating particles are commonly metaloxides, we present our results on nanoparticulate TiO2 and BaTiO3. We demonstrate how the permittivity may increase faster than expected due to the high surface of the nanoparticles, but that such composites are also very sensitive to air humidity, giving rise a high apparent value of the low-frequency permittivity, but with drastic effect on electrical loss. A chemical coating is shown to lead to strong improvements.

Also, we show studies on conducting nanoparticles. Especially, we demonstrate how “simple” percolation causes detrimental side effects, leading to overall reduction in actuation. Careful distribution of nanoparticulate metal in mesoporous silica-spheres leads to useful increases in permittivity, but the mechanical properties are not technologically useful. A “molecular composite” approach, in which the conducting nanoparticles are docked chemically to the backbone appears valuable. The achieved improvements seem to be all connected to avoiding a random distribution of the conducting entity, and instead achieving a constant nearest neighbour separation. A shielding of each conducting entity should also be encompassed. In combination, this leads to improved permittivity while leaving the breakdown strength and the stiffness unaffected, in all causing an activation of the polymer material towards actuation.

7642-17, Session 5

Challenges in microfabrication of DEAs

B. Balakrisnan, E. Smela, Univ. of Maryland, College Park (United States)

DEAs (dielectric elastomer actuators) have been demonstrated for meso- and macro-scale applications, but only a few devices have been shown at the micro-scale. The most commonly demonstrated micro-scale DEAs are diaphragms that bulge out of the plane of the wafer. Microscale devices would have many useful applications, including micro-robotics, micro-pumps, and micro-optical systems. In addition, an advantage of the micro-scale devices is that since the layers are thinner, the required driving voltages are reduced from kilovolts to tens or hundreds of volts. However, fabrication of micro-scale DEAs remains challenging. This is due in part to the fact that the vast majority of macro-scale materials and/or fabrication methods cannot be adapted to the micro-scale. On the micro-scale, the DEAs must be patternable, as well as compatible with other materials used during fabrication, such as sacrificial layers. Another practical issue in fabricating micro-scale devices is making connections to the top electrodes. It would also be desirable for the fabrication to be compatible with CMOS (complementary metal-oxide-semiconductor) driver circuits and other MEMS (micro-electro-mechanical systems). This article addresses the progress that has been made, as well as the challenges, in making MEMS-based DEAs. It also highlights the key areas in which additional research needs to be pursued.

7642-19, Session 5

Dielectric elastomer actuators: enhanced performance by systematic improvement of materials properties

M. Molberg, EMPA (Switzerland) and Ecole Polytechnique Fédérale

de Lausanne (Switzerland); Y. Leterrier, Ecole Polytechnique Fédérale de Lausanne (Switzerland); C. J. G. Plummer, C. I. E. Löwe, D. M. Opris, EMPA (Switzerland); J. E. Månson, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Dielectric elastomer actuators (DEAs) have attracted increasing attention over the last few years owing to their outstanding properties, e.g. their large actuation strains, high energy density, and pliability, which have opened up a wide spectrum of potential applications in fields ranging from microengineering to medical prosthetics. There is consequently a huge demand for new elastomer materials with improved properties to enhance the performance of DEA and to overcome the limitations associated with currently available materials, such as the need for high activation voltages and poor long-term stability. In recent work, we have investigated different dielectric and mechanical characterization methods for the determination of materials parameters that describe the actuation behaviour of dielectric elastomers. Three different elastomers were considered: an acrylic adhesive (VHB), a silicone rubber (PDMS) and a thermoplastic elastomer. The frequency dependence of the actuation performance of these materials was found to be dominated by the mechanical response rather than the dielectric properties, which remained relatively constant in the frequency range investigated. Such results nevertheless indicate that the overall performance may be improved by increasing the dielectric constant, which has led us also to consider composite elastomeric dielectrics based on the thermoplastic elastomer or PDMS and conductive polyaniline or ceramic (PZT) powder fillers. The potential of such materials as well as strategies to counter the adverse effects of increased conductivity and elastic modulus will be discussed.

7642-99, Session 5

Dielectric elastomer bending tube actuators with rigid electrode structures

F. Wehrheim, J. Meyer, Richard Wolf GmbH (Germany); H. F. Schlaak, Technische Univ. Darmstadt (Germany)

The common approach for dielectric elastomer actuators (DEA) is based on the assumption that compliant electrodes are a fundamental design requirement. Focused on tube-like and thin-walled actuator geometries those compliant electrodes cause an unwanted change of the actuator diameter during actuation. Additional support-structures could improve the radial stability but would decrease the total available space.

By following the ambition of maximum functional integration the concept of using a rigid electrode structure arises. This structure realizes both, actuation and support characteristics. The cross sectional shape of this actuator-tube is supported by common circular reference electrodes, which can be either axial-parallel or axial-coil-shaped.

The intended rigid electrode structure is based on a stacked DEA. As motivation and focused application a number of pairs of electrodes align axial-parallel within the wall of an elastic tube. The volume between the electrodes is occupied by an elastic dielectric. The axial adjoining alignment of the different actuator-axis' is expected to restrict the extension of the dielectric in x-direction (tangential). The dielectric should extend only in one direction.

By attraction of adjoining electrodes, the dielectric volume between those electrodes reduces. Because the original volume is expected to be non-compressible, the displaced dielectric is assumed to have the cross sectional shape of a circular segment. This shape is represented by the overlap sh, the area A2 and the volume V2. The overlap sh gives an applicable indicator for geometrical limitations and has been used to extract the first design rules regarding the electrode size x0·h0 and the aspect-ratio h0/y0.

Considering the strain in any direction the mechanical efficiency mech has been formulated. In combination with the relative displacement sh-rel further design aspects could be extracted by using this additional indicator.

With reference to DIN ISO 7743 a test for determination of the compressive stress-strain-characteristics has been applied.

For this test an up-scaled set-up was used. By variation of different parameter settings the transferability of the results to smaller dimensions has been shown within a limited range. Those practical results support the theoretical conclusions.

It should be noted, that the presented investigations consider exclusive the static behaviour of a DEA-setup with rigid electrodes. Further investigations will focus on the applicability to dynamic operation modes.

7642-20, Session 6

Optimized on dielectric elastomer actuator based on acrylonitrile butadiene rubber

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For many years, electroactive polymers (EAP) are popularly studied as alternate of the traditional electromagnetic actuators. They have characteristics as compliant, versatile, low density, and low cost. Specially, Dielectric elastomer has high capacity of actuation as human-muscle because of large deformation and large force. In this paper, we optimized the effects of additives and vulcanization conditions on the performance of a dielectric elastomer actuator. Previously, Synthetic elastomer based on Acrylonitrile Butadiene Rubber (NBR) was a material classified as a dielectric elastomer that can have its characteristics modified according to the requirements.

In this paper, we make an experiment about mechanical properties (Young modulus, stress relaxation), electric properties (dielectric constant, dielectric loss, breakdown voltage), and electric-mechanical properties (deformation of actuator). In the first experiment, this paper compares with two kinds of NBRs on the overall performances of the synthetic elastomer. We are carried out better NBR by analyzed results of experiments. Based on the results of the first experiment, Synthetic elastomer using selected NBR is optimized by DOE (Design of Experiments). We use table of orthogonal arrays that four factors were examined at three levels. Factors are composed of additives such as dioctyl phthalate (DOP), barium titanium dioxide (BaTiO3) and vulcanization conditions such as dicumyl peroxide (DCP), cross-linking times. Experimental results are analyzed by ANOVA (Analysis of variance). And the last, we accomplished 10% deformation and high force for an actuator.

7642-21, Session 6

The dynamic properties of tubular DEAP actuators

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Tubular actuators fabricated from dielectric electro-active polymers (DEAP) have been developed and optimized with focus on high volume roll to roll automated manufacturing techniques and processes. This paper will expand upon the established static performance characteristics of these actuators to include their response to time varying electrical stimuli, reporting the resulting dynamic mechanical and electrical behaviour. By measuring the mechanical outputs of the actuators such as force and stroke, produced by time varying electrical stimuli with different waveforms, the resonances as well as response time and electromechanical efficiency of the actuators can be obtained. Furthermore, to facilitate integration of the product into electromechanical systems, an electrical model of the actuating device is also presented. This measured and reported dynamic profile of the actuators can be used for implementing the DEAP actuators inside electrical and mechanical devices. Knowing the dynamic behaviour is fundamental to utilizing these devices in, for example, closed looped control systems. The techniques used to measure time dependent responses are established as a methodology and are used to provide consistent characterization of the behaviour of actuators.

7642-22, Session 6

Radially-expanding mechanism for dielectric elastomer actuators

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Dielectric elastomer actuators (DEAs) offer numerous benefits as high displacement smart material actuators. The output of a DEA film is typically characterised by a large area expansion and a smaller transverse displacement. Consequently, their application is often limited by difficulties in resolving area expansion strain into a usable output. DEAs also require pre-strain in order to achieve optimal performance.

In this paper, Hoberman's radially-expanding mechanism is used to form a novel DEA structure. The mechanism is composed of a number of repeating angular scissor-links which resolve DEA area strain into a uniaxial displacement and have intrinsic pre-straining capabilities. This allows the Hoberman mechanism to be exploited as an actuator. Additionally the structure can be used as a device for pre-straining dielectric elastomer films. The mechanism's performance as both a DEA and a pre-strain device is investigated through kinematic optimisation and stress/strain distribution analysis via photoelasticity and finite element modelling. These analyses show that there is a design trade-off between biaxial strain uniformity of the DEA layer and the mechanism's mass and frictional losses.

The development of prototype actuators using this mechanism is described along with the results of experimental tests. These tests demonstrate that the prototype actuators resolve area expansion strain into a uniaxial displacement (which can be linear or rotary) at the cost of mechanical losses. The performance of the mechanism is compared with existing linkages such as the bowtie configuration and potential novel applications are discussed.

7642-23, Session 6

Processing, microstructure, and properties of a fiber-reinforced dielectric elastomer actuator

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Dielectric elastomer actuators are often characterized by large free strain, and equally low blocked stress output. One hypothesis would be that the addition of fiber reinforcement would increase the blocked force output at the expense of free strain. Numerical values to quantify the resulting tradeoff could potentially benefit dielectric elastomer research and lead to a host of useful materials and devices.

One candidate for a fiber-reinforced device is the McKibben-style actuator. Based upon the work of Rivlin in characterizing the effect of "inextensible fibers" on passive elastomers, the concept has been recently been expanded to include effects of an applied electric field on the McKibben structure. Recent analyses by McKay and Goulbourne predict axial strains in the vicinity of 5% for fiber-reinforced cylindrical dielectric elastomer actuators. By means of finite element analyses, McKay predicted increased axial displacement with reduced elastomer layer thickness. McKay's analysis also predicted a change from an axially elongating actuator to an axially constricting actuator depending upon fiber orientation. In addition to axial performance predictions, the reduction of elastomer thickness results in a profound reduction of operating voltage of dielectric elastomer devices. The analyses predict that many potential advantages can be achieved by control of film thickness and fiber angle in a fiber-reinforced cylindrical actuator. While the analyses show promise, use of commercially available material forms, such as polyacrylate film products, limits the ability of researchers to produce devices capable of testing analytical predictions.

A multistep process has been developed using uncured elastomer precursor materials and tow placement strategies to produce cylindrical actuators with precise control over elastomer thickness, fiber orientation and fiber fraction. Elastomer thickness reductions of as much as 80% over commercially available films have been obtained. A number of McKibben-type actuators were fabricated and tested for electrode continuity, elastomer dielectric properties, fiber-elastomer composite material mechanical properties, and actuator performance under an applied electrical and stress field. Actuator results are presented in terms of blocked stress and free strain with performance of actual specimens compared to analytical predictions.

7642-24, Session 6

Graphite/PDMS stretchable electrodes for dielectric elastomer actuators

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Dielectric elastomer actuators (DEAs), consisting of an elastomer sandwiched between two electrodes and having large in-plane expansion upon the application of a voltage, require electrodes that are compliant. Currently, the most commonly used electrode material is carbon grease. However, carbon grease smears easily and is difficult to pattern, so an alternative material is required. This paper outlines the fabrication and performance of a novel graphite/ polydimethylsiloxane (PDMS) composite electrode material. This new material has a Young's modulus of only 0.43 MPa, has conductivities as high as 0.02 S/cm, and is capable of reaching strains as large as 50% before failure. Unlike other composite electrode materials, the elastic modulus of the graphite/PDMS increases only slightly at the loadings required to make the material sufficiently conductive for DEAs. Under repeated strain cycles, the modulus remains constant, and the conductivity actually increases. Furthermore, the graphite/PDMS composite is patternable and will not rub off. DEAs were fabricated from PDMS using these electrodes, and the strains were comparable to those in PDMS devices made using carbon grease. This material may also find applications in areas such as flexible electronics, robotics, strain gauges, and sensors.

7642-25, Session 6

Effects of conductive particles on the actuating behavior of dielectric elastomer actuator

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Dielectric elastomer, also known as electroactive polymer artificial muscle, has shown considerable promise for a variety of actuator applications. However, the need for high actuating electric field of the dielectric elastomer actuator greatly limits its practical applications. A reduction of the actuating electric field may be achieved according to develop elastomers with high permittivity. The effects of conductive particles on the actuating behavior of silicone rubber-based dielectric elastomer are studied in this work. Three different materials, which are carbon nanotube, short fiber, and carbon black, respectively, are used to increase the overall permittivity of the composites. These composites are characterized by dielectric spectroscopy, scanning electron microscopy, tensile mechanical analysis, and electromechanical transduction tests. The effect of variation in filler loadings on the complex and real parts of permittivity are distinctly visible, which has been explained on the basis of interfacial polarization of fillers in a heterogeneous medium. The phenomenon of percolation was discussed based on the measured changes in permittivity and morphology of composites at different concentrations of these particles.

7642-26, Session 6

Thermodynamic design model for dielectric elastomer actuators

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Dielectric Elastomer Actuators (DEAs) are a promising actuation technology for small mobile robotics due to their high force-to-weight

ratio, high energy density (per volume) and potential for high energy conversion efficiency. Nonetheless, designing such systems requires a good understanding of the actuators' thermodynamic performances in order to optimize energy usage for a given actuator weight and volume. This paper proposes a design model of DEAs' thermodynamics, DEAs that are controlled under three different modes of operation: constant voltage, constant electrical field and constant charge. Accompanied by a thorough experimental validation, this analysis is useful for design work involving energy-related calculations, since it explains how DEA performance is affected by the three modes of operation and by material dependant loss mechanisms.

A thermodynamic analysis of a uniform DEA is conducted assuming no losses. Fundamental equations are derived for actuator mechanical work, energy consumption and efficiency for each of the three modes of operation. The analysis reveals that DEAs use stored energy in the form of electric charges, much like internal combustion engines do in the form of compressed gasses. This work indicates that the constant voltage and constant charge modes have opposite performance characteristics. In fact, constant voltage mode involves high mechanical work but low efficiency, while constant charge mode is associated with low mechanical work and high efficiency. The constant electrical field mode results in an average performance, positioned between the performances of the other two modes. The effect of energy recovery on DEA efficiency is also theoretically addressed as it appears physically impractical, due to heavy system weights and limited performance gains.

Performance predictions of the thermodynamic analysis are completed with a broad range of experimental data obtained from oblong-shaped DEAs, made in both VHB 4905 acrylic and Nusil CF19-2186 silicone. A work-cycle test bench was implemented to achieve complete performance mapping of the constant voltage and constant charge processes. Similar to motor efficiency maps, actuators at different nominal voltages, actuator extensions and speeds are tested, and overall energy conversion efficiencies are established. The experimental performance trends are corroborated by the thermodynamic analysis and the differences are explained by material-dependant electrical and mechanical losses, the magnitudes of which are evaluated experimentally. Finally, the design model is demonstrated through the preliminary design of a DEA rotary motor.

Results show the design model to be an interesting tool for actuator preliminary design. The model also provides quantitative values of actuator loss mechanisms, which help minimize energy consumption in geometric design purposes. This work should be of interest to the entire DEA community as it is a first cut DEA design tool.

7642-65, Poster Session

Novel cellulosic gel preparation for using in electro-responsive applications

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Celluloses used in the field of electro-responsive applications are known as the "Electroactive-paper (EAPap)". In this work, physical and chemical cellulose gels are prepared and studied for the effects of crosslinking ratio (CR) and ageing time (tag) on the mechanical properties of the cellulose gels. An ionic liquid,1-butyl-3-methylimidazolium chloride (BMIMCl), was used as an effective cellulose solvent for EAPap. The crosslinking reaction conversion increases with increasing CR and tag. The crosslinking reaction products are ketone linkages and water molecules as by product. The difference in optical properties is observed and is related to the relative amount of ketone linkage as confirmed by FTIR-ATR. By-product water molecules exhibit plasticizing effects which decrease the storage modulus (G') after 1 aging day The outward migration of the by-product water molecules causes slightly increasing of G' after 15 aging day due to a closer packing. In addition, by-product water molecules create cellulose aggregations and increase disordered region that contributes to the increase in electrical conductivity based on the ion migration. In addition, electromechanical properties of our cellulose gels will be shown and compared with other electroactive material systems.

7642-96, Poster Session

Electric field modelling of DEAP material with compliant metal electrodes

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Electrical breakdown is the main failure mode for DEAP materials. The phenomenon occurs when the electric field in a material becomes greater than its dielectric strength and the insulating barrier properties are exceeded.

The electrodes, ideally, must be highly compliant, from both an electrical and mechanical perspective. Compliant metal electrode technology, derived from micro-machining and screen printing, achieves compliance by using a corrugated profile. Increases in the electric field distribution due to the profile(s), when compared with a parallel plate type compliant electrode, might possibly cause a greater incidence of electrical breakdown.

In this contribution, the electric field and surface charge density characteristics of compliant metal electrode-based DEAP material are investigated. A mathematical model of the electric behaviour in the complaint conductor and dielectric are initially developed using classical electrodynamics theory. This model is then implemented in a finite element simulation package, COMSOL. Initially a comparison is carried out between the electric field and surface charge density characteristics of a compliant parallel plate type material with a complaint metal electrode-based material with sinusoidal corrugations. The possible affects that impurities in the elastomer might have on the electric field behaviour are then examined. Only two defects are addressed here - penetration of the metal electrode into the body of the elastomer and air bubbles in the body of the elastomer.

7642-97, Poster Session

Active vibration control of periodic disturbances using a DEAP damper

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Tubular dielectric electro-active polymer-based actuators have many possible applications. The use of such a device to provide active vibration control, either by itself or as a complimentry approach to passive damping, potentially has a wide market.

In this contribution a DEAP core-free tubular actuator will be examined for its ability to carry out the active vibration control of periodic vibratory disturbances. A potential problem with the use of any DEAP devices to damp periodic vibrations, not just the actuator used here, is that for periodic input voltages the mechanical output of the DEAP actuator will be the square of the periodic input. This will result in an output with several harmonics. Therefore from a vibration damping perspective not only does the first harmonic of the periodic disturbance need to be controlled but also subsequent harmonics to achieve the 'best' vibration damping performance across a range of frequencies.

First of all the dynamic characteristics of the core-free tubular actuator used are introduced. The dynamic characteristics provide an indication of the frequency range over which active vibration control might be successful in damping vibrations. Feedforward active vibration control is considered here and it is initially shown that a d.c. offset of the controlled voltage signal can be used to improve the damping characteristics of the device. Two approaches to remove the vibrations due to higher harmonics are examined - (a)linearization of the control signal, and (b) dedicated individual feedforward controllers for each harmonic.

7642-98, Poster Session

Ultra high electrostriction behavior of electroactive thermoplastic elastomer gels by in-situ tracing microstructural change during electromechanical actuation

C. M. Koo, S. M. Hong, Korea Institute of Science and Technology (Korea, Republic of)

Althought the dielectric elastomers have been able to actuate electrostrictively more than 50% driven mainly by a Maxwell stress effect and by the electrostrictive effect, relatively high applied electric fields (>50V/mm) is the biggest challenge for the real applications. The most efforts for reducing the operational voltage have been focused on increasing a dielectric constant and decreasing a compressive modulus because both are known to be key parameters in the Maxwell stress effect of the dielectric elastomer.In this work, we illustrate a different example where the electrostrictive effect dominates the actuation of the dielectric elastomer resulting in a high electrostriction coefficient as well as in a high electrostrictive strain at relative low operational voltage.

7642-100, Poster Session

Development of high strain electro-active polymer actuators via optimization of the pore size of the conductor network composite layer

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For electro-active polymer actuator devices (EAPADs), the porosity of the conductor network composite (CNC) is critically important as it influences the mobility of the ions within the device and thus effects the actuation speed and the efficiency (i.e. strain) of the actuator. We have employed the layer-by-layer (LbL) assembly technique to incorporate spherical metal nanoparticles into the CNC layer. The size and geometry of the metal nanoparticles controls the pore size of the CNC layer. In this work, the electromechanical response of EAPADs is studied as a function of the size of the incorporated metal nanoparticles. Significant improvements in the actuation speed and strain were observed upon incorporation of larger metal nanoparticles in the CNC layer, verifying that optimization of the size of the metal nanoparticles leads to improvements in the efficiency of the EAPADs. We have studied samples containing different size metal nanoparticles and have observed that a large enough pore size facilitates improved motion of the ions from one electrode to another; which leads to a faster actuation speed and higher strain. For example, under application of an electric field (4 V), samples containing ~220nm diameter nanoparticles exhibited higher strain (12.4%) than samples containing ~3nm diameter nanoparticles (6.9%).

7642-101, Poster Session

Preparation and characterizations of PVDF/MWCNT nanocomposites

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We investigated the interrelationships among the crystal structures and the physical /ferroelectri/piezoelectric/rheological properties of a thermoplastic composite based on poly(vinylidene fluoride)(PVDF)/multiwall carbon nanotubes(MWCNT). Beta-form crystal increased with CNT contents, passing through a peak, and decreased. the structural changes depended on the CNT contents. the PVDF/MWCNT with 0.2wt% MWCNT contents had the highest value of piezoelectricity. the rheological properties were also presented in order to understand the dynamic behaviors of the composites

7642-102, Poster Session

Electrically driven PEDOT/PSS actuators

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Free-standing films made of poly(3,4-ethylenedioxythiophene) doped with poly(4-styrenesulfonate) (PEDOT/PSS) were prepared by casting water dispersion of its colloidal particles. Morphology, water vapor sorption, and electro-active polymer actuating behavior of the resulting films were investigated by means of atomic force microscopy (AFM), sorption isotherm, thermal mechanical analysis (TMA), and electromechanical analysis. It was found that the PEDOT/PSS film sorbed 60% of moisture at relative water vapor pressure of 0.95. Upon application of 10 V, the film underwent contraction of 2.4% in air at 50% relative humidity (RH) which significantly increased to 4.5% at 90% RH. The principle lay in desorption of water vapor sorbed in the film due to Joule heating, where electric field was capable of controlling the equilibrium of water vapor sorption. The film generated contractile stress as high as 17 MPa under isometric condition and work capacity attained 174 kJ m-3, where Young's modulus of the film increased from 1.8 GPa to 2.6 GPa by application of 6 V at 50% RH.

7642-103, Poster Session

Effect of strain on the electrical conductivity of a styrene-butadiene rubber

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When the carbon black-filled rubbers are stretched, the electrical resistivity increases at lower extension ranges, and then it decreases with further extension. This complex behavior is attributed to the morphology changes of carbon blacks during extension, i.e., breaking and forming conducting paths.

In this study, highly conductive carbon blacks were selected and they were compounded into a specially-designed styrene-butadiene rubber (HSBR) with Tg of 38ºC. The loading level was of 5phr, 10phr, 15phr, and 20phr, respectively. The electrical resistance was measured for all compounds at room temperature, 40ºC, and 80ºC. And the resistivity was also monitored with tensile straining. The electrical conductivity increased as the content of carbon blacks and temperature were increased. The resistivity increased with tensile loading, and it further increased during unloading.

7642-104, Poster Session

Integration of dielectric elastomer stack actuators into micro systems

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Using dielectric elastomer stack actuators the electrical contact to each conducting layer is a major concern. In order to integrate these actuators inside micro systems e.g. microfluidic systems compatibility to micro fabrication processes is required. The contact resistance and number of connected layers influence the overall actuator performance directly. Less active electrodes decrease the generated electrostatic pressure of the actuator. High contact resistance negatively impacts the dynamic actuator behavior.

Conventional interconnection processes like pulling copper wires through the feeding lines, the contact ratio is in the range of 60% to 90%, depending on the film thickness of the dielectric layer. Furthermore, this process is not compatible to standard micro fabrication technologies. Therefore, a new connecting process is developed to achieve a high contact ratio and a low contact resistance.

In this paper we evaluate a process based on electroplating for connecting dielectric elastomer stack actuators and present a measurement system to characterize the number of connected layers.

The performance of an electroplated contact is defined by the number of connected layers and the contact resistance between electroplated copper studs and graphite electrodes. It depends on different parameters like the cross sectional area of the electrode layers for connection and therefore on the layer thickness. Using multiple small contacts instead of a single large one the performance of the contact can also be positively influenced.

The full paper will include detailed information about the electroplating process, measurement setup and measurement results.

7642-106, Poster Session

Dependence on boundary conditions for the actuation characteristics of the dielectric elastomer actuators

M. Kollosche, H. Ragusch, G. Kofod, Univ. Potsdam (Germany)

One type of polymer actuators are the electric-field-actuated dielectric elastomer actuators (DEA), which can be considered as soft rubber capacitors. The actuation properties of electro-active polymers are strongly dependent upon the properties of the constituent materials and preparation methods. We present electro-mechanical characterizations of dielectric elastomer actuators (DEA) prepared of a thermoplastic tri-block copolymer, poly-styrene-ethylene-butadiene-styrene (SEBS) with comparison to the commonly used VHB-4910 tape. This study focuses on the effects of the boundary conditions, stiffness and voltage ramp on the breakdown properties of different SEBS materials, and compares with similar measurements on VHB-4910. Experiments were carried out on SEBS Dryflex 500120, 500040 and Dryflex 500000, provided by Elastoteknik AB (Sweden) as a dry granulate solid. The solid elastomer was dissolved in a suitable solvent and dropcast into the desired shape. A very strong dependence of the electromechanical properties upon the voltage ramp was observed, which is explained by visco-elastic influences. Measurements of the electromechanical properties of SEBS DEAs under conditions of constant strain and constant force are performed. These measurements show an actuation strain of around 10%. SEBS was thus found to have a number of advantages. The physical cross-linking allows for a multitude of processing options, and generally simplifies casting-based processes in comparison to chemically cross-linked elastomer systems. Further, the reduced visco-elasticity compared to VHB 4910 should result in actuator structures of improved conversion efficiency.

7642-107, Poster Session

Novel approach to tunable diffractive transmission gratings based on dielectric elastomer actuators

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Dielectric elastomer actuators (DEA) made of thermoplastic tri-block copolymer poly-styrene-ethylene-butadiene-styrene (SEBS) and of the commonly used VHB-4910 tape were studied for voltage-tunable optical transmission grating applications. Compared to ready-to-use VHB tape, the dry granulate SEBS (Dryflex, Elastoteknik AB, Sweden) must be dissolved in a suitable solvent and dropcast into the desired shape. For DEA manufacturing, the material was pre-stretched, fixed to a stiff frame and covered with appropriate stretchable electrodes. Experiments are performed to implement master grating structures on DEA films via different nano imprint techniques, e.g. hot embossing. The master structures were produced by a holographic method which writes sinusoidal surface relief gratings into photoactive films of azobenzene polymers. Since the actuation strain of the DEA strongly depends on the boundary conditions, e.g. pre-stretch and geometry, the desired voltage-controllable deformation of the grating can be optimized via manufacturing parameters, both in material preparation and in grating implementation. A full characterization of the deformation of the grating shape is required, both regarding the grating pitch and the depth modulation and surface structural distortion, since these effects could lead to decreasing diffraction efficiency and lower beam quality. With properly chosen manufacturing parameters, a shift in a 1µm grating period of up to 10% can be found. A model based on independently measured material parameters is shown to describe the optical behavior.

7642-108, Poster Session

Modeling ionic polymer diluent response in sensing

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An ionic polymer transducer (IPT) may be employed as either an actuator or sensor, where the bending mode of transduction has frequently been studied. However, the electromechanical response is not symmetric; the voltage signal required to induce a given tip displacement in actuation is higher than that generated for the same deformation in sensing by an order of magnitude or more. Thus, the physical mechanisms responsible for actuation and sensing are necessarily different. Because IPTs display sensing response for any mode of deformation (bending, tension, compression, shear), it is postulated that the mechanism of streaming potential dominates sensing response. The source of the streaming potential is the flow of entrained fluid and cations (electrolyte) with respect to the electrodes expected for any mode of deformation. In this study flow is assumed to be linear and Newtonian. Investigation will focus on the trends in the final position of water molecules in response to IPT deformation. Implications of these trends in relation to physical regions of the polymer nanochannels will be explored.

7642-109, Poster Session

Photo/electro-responsive materials based on spiropyran dyes, terthiophene, PEDOT, and thiophene hybrid materials

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Thiophene derivatives are ideal building blocks for many synthetically processes for their widely studied conductive properties and for their ease of characterisation. Considering this, and our extensive experience with spiropyran derivatives, the idea to integrate the attractive properties of these two interesting molecular families within the same structure was proposed. Polythiophenes bearing covalently attached receptor sites are particularly interesting to us as they have properties that make them particularly desirable as chemical sensors [1, 2]. Using electrochemical and chemical synthesis pathways [3, 4], it is possible to produce and to characterize a family of new materials qualified by similar physico-chemical properties and in particular, conductivity.

The new composite monomers constituted by the spiro-group and the thiophenic function, were prepared by a new coupling process developed in our laboratory. The subunits were then polymerized by electrochemical synthesis on the ITO layers and by vapour phase polymerization (VPP) [3] on the other materials. The electrochemically-functionalized surface was the well-known Indium tin oxide (ITO) layer; it was then followed by a poly-N-isopropylacrylamide (PNIPPA) structure, self-polymerized by a 254nm UV light source and subsequently treated in a special chamber prepared for the VPP technique that allowed the insertion of the combined polymers into it. The physico-chemical properties of the new materials were studied under a range of different conditions, using different buffer solutions, different ions (Co2+, Cu2+ and Ni2+) and various light sources (LED, UV, visible light), in order to analyze all the features in as much detail

as possible. Subsequently the new functionalized polymers will be investigated for binding behaviour with a number of biological entities, such as amino acids, small peptides and proteins [5].

To analyze the binding properties of the new materials FT-IR and Raman analysis techniques were used. Furthermore complexation and releasing properties were studied under electrochemical and photochemical excitation [6].

Several applications of these new materials can be proposed on the basis of their switchable photochromic properties; first of all in the field of the sensors and in second instance in the field of the smart materials where binding with guest species can be turned on/off photonically, and physical properties such as conductivity modulated using light.

ACKNOWLEDGEMENTS

The authors would like to acknowledge support for this research by Science Foundation Ireland under CLARITY (Centre for Sensor Web Technologies) grant 07/CE/I1147.

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7642-110, Poster Session

Electro-mechanical properties of novel large strain PolyPower film and laminate components for DEAP actuator and sensor applications

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A novel large strain PolyPower® compliant electrode has been manufactured and tested. The new electrode design is based on the anisotropic corrugated electrode principle with a corrugation profile designed to enable up to 100 percent linear strain of PolyPower compliant electrodes. Specifically, corrugations height-to-period ratio in the 1.1 range allows stretching the thin metal electrode more than 100 percent without inducing any substantial damage to it. Based upon this new design, PolyPower films and laminates are large scale manufactured and used to fabricate PolyPower InLastor actuators and sensors capable of withstanding large strain conditions. The metal electrode is applied onto the corrugated surface of silicone elastomer film.

Experimental measurements made with single and multi-layer dielectric electro-active polymer (DEAP) PolyPower laminates will be presented. Electrical and mechanical properties of the electrode will be discussed. Stress and capacitance measurements as a function of strain and corrugations height-to-period ratio are used as a basis to analyze the properties of the laminates. It can be shown that the degree of anisotropy of compliant electrode affects the stress and capacitance dependence as a function of axial strain in the compliance direction. The degree of anisotropy of the electrode depends very much on the thickness of the coatings applied to the corrugated surface of elastomer film. This degree determines the conversion ratio of Maxwell pressure into actuation pressure in the direction of compliance. Results of analysis of visco-elastic properties of fabricated laminates are presented in the form of hysteresis loss diagrams and stress-relaxation measurements.

7642-111, Poster Session

Scavenging energy from human motion with tubular dielectric polymer

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Scavenging energy from human motion is a challenge to supply low consumption systems for sport or medical applications. A promising solution is to use dielectric polymers to scavenge the mechanical energy during walk. Indeed, the high energy density of dielectric polymers, i.e. few J.g-1, is favourable to the miniaturization and the integration of micro power generators. In this paper, we present a new design of scavenger which is the first step toward an integration of dielectric generators into textiles. Indeed, our scavenger is composed of N tubular dielectric polymers attached to the fibber of a kneepad. This structure is localized in front of the knee where the maximum of strain is observed. Commercial silicone poly(dimethylsiloxane) Detakta 1505 tubes are used to create the generator. Compliant electrodes are realized with a silver grease Circuit Work 7100. This grease is hand brushed on and into the dielectric tube to create a variable capacitor. As dielectric polymers are passive materials, scavenging energy need the realization of energetic cycles with a poling voltage. Thus, energetic cycles under a poling voltage less than 1500V have been realized. These tests validate the analytic modelling presented in this paper. Finally, for an energetic cycle at constant charge Q, one relaxed tube is able to scavenge up to 29µJ with a poling voltage of 1000V. Thus, on the available area in the front of the knee, i.e. 10cm², 6 tubes can harvest 174µJ at 1Hz, enough to supply a low consumption system. Tests on pre-stressed structures are under development.

7642-112, Poster Session

Understanding the role of surface and intermediate layer impedance in mechanoelectric property of IPMC

K. J. Kim, R. Tiwari, Univ. of Nevada, Reno (United States)

Despite of large amount of research being reported on IPMCs there is still a need to understand the mechanoelectric response. Understanding the mechanoelectric behavior may help in design and development of the polymer and enhance its applicability as well. Since IPMC manufactured through electroless deposition have three distinct layers: electrode, intermediate and polymer, the behavior of the material is governed by the physics of each layer and the coupling between them. Though the layers are distinct, the measurements to understand the role played by individual layer are not plausible. In this paper we tend to study the role of surface non-linearity due to distributed impedance and intermediate layer impedance due to the metal dispersed in the polymer. The model is developed incorporating these impedances to predict the mechanoelectric behavior of IPMC. The predictions are validated through series of electrochemical analysis. Based on the model and experimental results we can conclude that increasing the overall capacitance and decreasing surface impedance results in improved mechanoelectric property of IPMC.

7642-114, Poster Session

Electromechanical properties of silicone-PZT (lead-zirconate-titanate) composite

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Dielectric elastomer composites are widely used electromechanical actuators. Compounding of dielectric elastomers with electroceramics

helps to decrease the required electric field. In this work, silicone rubber was compounded with Lead- Zirconate-Titanate (PZT) electroceramic powder by the help of a silane coupling agent for better compatibility between organic ceramic and inorganic polymer. Modified PZT was added to silicone rubber with variable amount to study the effect of ceramic concentration on composites properties. Morphology of the composites was characterized by scanning electron microscopy, mechanical properties of the samples were studied by uniaxial tension tests, and their dielectric properties were compared through dielectric measurements. The results showed that at about 10 wt% of PZT loading dielectric permittivity is higher for this composite compared to those for composites with lower or even higher loading of PZT.

7642-115, Poster Session

High-resolution tactile display operated by an integrated 'smart hydrogel' actuator array

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Within the last thirty years microelectronics significantly changed our life and work. Certainly it is consequent to ask about the potential of microelectromechanical systems (MEMS) containing thousands of components. Here, we introduce a high-resolution tactile display based on the integration of 4,225 actuators with a density of 300 actuators per cm^2 into an array displaying both visual and palpable information. The actuators are fabricated simultaniously by UV-patterning. Active polymeres called "Smart Hydrogels" are used as actuators which are sensitive to changes in the temperature. The high resolution temperature field is generated by an optical- or resistive interface that is controlled by a computer. An actuator pixel changes the color from transparent to opaque providing a visual monochrome functionality. It changes as well the altitude and the elasticity. Therefore the display is able to generate artificial impressions about contours, textures, profiles and the softness of a surface. This surely is a basic feature necessary for future haptic applications.

7642-116, Poster Session

Utilization of electroactive polymer actuators in micromixing and in extended-life biosensor applications

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Polypyrrole (PPy)-based microactuators hold a promise for a wide variety of engineering applications from robotics and microassembly to biosensors and drug delivery systems. The main advantages of using PPy/Au actuator structures (vs competing solid-state actuator technologies) include ease of fabrication, low actuation energy, and large motion range of microactuators. We present advances in two areas of application - in the extended-life biosensor platform and in micromixers.

For some patients it's extremely important to have a continuous monitoring of their physiological levels (for example, glucose levels in diabetic patients). Enzymatic biosensors typically can work for several days before they deteriorate and should be replaced by fresh biosensors. Our approach is to use an array of biosensors protected in cavities covered by individually-addressed PPy/Au valves. Protected biosensors do not deteriorate and can be stored for many months. The biosensors are opened sequentially - once the working biosensor starts to deteriorate, the fresh biosensor can be activated on-demand by opening the corresponding protected cavity. The microvalve lids are opened by the application of 1V bias. Thus, in-vivo biosensor platform operation can be extended from days to months - the platform lifetime is only limited by the number of biosensors in the array. An array of about 90 covered reservoirs is required for six months of continuous operation (if a fresh biosensor is activated every 48 hours). Such an array can be created on a chip of only several cm2 since each protected cavity is only 200 microns in diameter. We will discuss various platform designs, validation, sensor immobilization, and initial test results.

We also fabricate and utilize PPy/Au microactuators for micromixing. Mixing and homogenization of solutions is critical in analytical and diagnostic applications that use microfluidics - such as "Lab on a Chip" (LOC) technology. One of the limitations for mixing fluids in small volumes is the absence of turbulent flow (so-called low Re regime). In such regime the fluid behaves as an essentially viscous substance - i.e. mixing of two adjacent layers in the fluid is limited to diffusion only - there is very limited advection. Typical approach employed in many LOC platforms is passive mixing - two fluid streams (intended for mixing) are allowed to collide, to move through some "obstacle course" in microchannels, or to flow side-by-side - operations that are designed to reduce an effective diffusion distance in the fluids and to facilitate mixing. Such passive mixing typically requires long channel length which is problematic for microchips where size limitations are important. Our alternative approach is to use PPy/Au active micromixers. We will present promising initial results that demonstrate feasibility of micromixing in a droplet of fluid.

7642-117, Poster Session

Tunable stiffness and damping modules using dielectric elastomers

S. Dastoor, M. Cutkosky, Stanford Univ. (United States)

The passive compliance and damping inherent in dielectric electroactive polymers (EAPs) are an important aspect of their potential as muscle-like actuators. The ability to actively tune these parameters is useful in a variety of situations, from dynamic locomotion of legged robots to adjustable suspension elements to human- safe robot designs. Previous work on tunable elements has relied on complex mechanical systems or fluid suspensions, neither of which are ideal for compact or lightweight platforms. Our research presents an electrically-variable stiffness and damping module based on an EAP actuator. This module is based on a novel actuator design using a pre-strained commercially available VHB acrylic film (3M), a deposited carbon-based electrode, and multi-material support structures. The manufacturing process for these structures and the entire modules, from material preparation to final assembly, was developed and fine-tuned for robust, reliable performance. In addition, control electronics were modeled and developed to adjust these passive parameters. Modeling of these modules is compared to data obtained from a custom-built dynamic mechanical analyzer that is used for experimental testing and characterization of the modules, including their effective range of stiffness and damping values. Finally, their feasibility for use in the suspension of a perching unmanned aerial vehicle (UAV) as a proof-of-concept platform is examined.

7642-118, Poster Session

Optimization on the structure of micro-pumps driving by IPMC

H. Ding, Q. He, M. Yu, D. Guo, Z. Dai, Nanjing Univ. of Aeronautics and Astronautics (China)

Four different designs of micro-pumps driving by IPMC, disc, S, strip, and sector shapes, were designed. A series of IPMC-based strip actuators were prepared, their actuation displacements were measured by a laser displacement sensor, and the related bending moments were calculated. Under ANSYS software, some parameters of a pump such as withdrawal volume and working pressure were simulated by changing the radius, thickness, and shape of IPMC diaphragm and driven voltage. Results present that, comparing with the other three kinds of diaphragms, the sector-shaped one produces a larger withdrawal volume ;with the increasing of diaphragm radius, the withdrawal volume increases; with the increasing of diaphragm thickness, the working pressure increases; with the proper increasing

of voltage, both the withdrawal volume and the working pressure effectively increase.

7642-119, Poster Session

The area of allowable states in Mooney-Rivlin type dielectric elastomer generators

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Dielectric elastomer(DE) could be used to design and fabricate generator, which has been verified by experiments. The function principle of DE generator is contrary to the one of DE actuator. By imposing a low volt to the dielectric elastomer membrane to produce pre electric particles on the two facing surfaces. Then apply mechanical force to the sides of the membrane to produce pre-stretch. As the result of pre-stretch, the thickness of the membrane becomes thinner and the capacitance increases, mechanical energy is converted to elastic energy. After the mechanical force is canceled, because of elasticity the thickness of membrane increases while the capacitance decreases, elastic energy is converted to electrical energy, there by a cycle of conversion from elastic to electric energy is accomplished. Researchers have always been expecting to find a model that can well predict and evaluate the performance of dielectric elastomer generator. Suo et al. proposes the typical failure model of neo-Hooken type dielectric elastomer generator and calculates the maximal energy converted in a mechanical and electrical cycle. In this paper, we demonstrate the area of allowable states of various Mooney-Rivlin type dielectric elastomer generators, which can be employed to direct the design and fabrication of Mooney-Rivlin silicone generator, and the results seem to support Suo's theory.

7642-121, Poster Session

EAP generators

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In these days the micro power generators (MPG) are researched frequently. MPG generally divided for Piezo generators, electromagnetic and EAP (Electrically activated polymer) generators. Among them, EAP has the unique characteristics of flexible, versatile, silent and light. Research for EAP Generator has just started, so analysis of EAP Generator is still rare. We presented the circuit for harvesting of the electric energy, using a sequence of the charger`s flow and the equivalent voltage-capacitor model. After that we verified that EAP material has large specific energy density than other smart materials. We simulated the state of electric energy with Smartspice of Silvaco company. And we committed the basic experiment for knowing tendency of rising voltage and verification of energy generation.

7642-27, Session 7a

IPMC: recent progress in modeling, manufacturing, and new applications

K. J. Kim, Univ. of Nevada, Reno (United States)

Ionic Polymer-Metal Composites is a smart polymer-based actuator and sensor that was introduced more than fifteen (15) years ago. Since then significant progresses have been made to understand the coupling mechanisms of electromechanical and mechanoelectrical couplings. More recently the focus was on controls and manufacturing of IPMCs for various applications. In this paper we present the recent progress in modeling, manufacturing including scale-ups, and new applications made by the researchers at University of Nevada, Reno.

7642-28, Session 7a

Experiments with self-sensing IPMC actuating device

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In earlier work we proposed the realization of a self-sensing IPMC by patterning its surface in a way that separates the actuator and the sensor parts. More specifically it is possible to measure the change in resistance of a part of the surface electrodes and this information can be used as feedback for the actuator part which, for example, may lead to closed-loop control of the IPMC actuator. In this paper experimental results about electrical properties (e.g. impedance and capacitance) of the surface of the sensing part are presented. We present dynamical variations of capacitance and impedance of IPMC sensor. Paper at hand compares different methods for separating sensor and actuator parts and introduces some results to verify preliminary electro-mechanical model.

7642-29, Session 7a

Conducting polymers as simultaneous sensor-actuators

T. Fernandez-Otero, G. Vazquez, L. Valero, Univ. Politécnica de Cartagena (Spain)

The electrochemical reaction for the oxidation/reduction of any prevailing anion (A-) interchange-conducting polymer (CP), can be written as:

[CPa+(A-)]s + n(A-)aq+ mH2O ↔ [(CP(n+a)+)(A-)n+a (H2O)m]gel + (n e-)metal

The reaction includes all the electrochemical properties and electrochemical applications of those non-stoichiometric and reactive materials. The progressive change of volume between [CPa+(A-)]s and [(CP(n+a)+)(A-)n+a (H2O)m]gel taking place under flow of a constant current originates the development of artificial muscles. The muscle potential shift during any actuation must be influenced by any chemical or physical variable acting on the chemical reaction. As expected the evolution for any device (bilayer, triple layer or complex design), the muscle potential changes if we modify: the electrolyte concentrations, the temperature, the weight of objects attached to the bottom of the muscle, or the current flowing through the device. Lineal evolutions are obtained for the electrical energy consumed by the artificial muscle to cross over a constant angle as a function of the studied experimental variable. Both signals, the actuating current and the muscle potential response, are included by the same two connecting wires, opening a new paradigm for electrochemical devices. Those results underline the simultaneous sensing and actuating capabilities of the device. If a muscle moves freely meeting, touching, and pushing an obstacle the muscle potential steps, proportionally to the mechanical resistance of the obstacle, at the touching moment: this is a tactile muscle. The tactile muscle mimics natural muscles: it is constituted by a reactive material including organic polymers and water, and involves electric currents, chemical reactions, conformational movements in chains, ionic and aqueous interchanges. The driven electrochemical reaction includes, simultaneously, actuating and sensing properties.

7642-30, Session 7a

MEMS-based fabrication of multiple-degree-of-freedom ionic polymer-metal composite actuators

Z. Chen, X. Tan, Michigan State Univ. (United States)

Ionic polymer-metal composites (IPMCs) are soft actuation materials with promising applications in robotics and biomedical devices. In this paper, a MEMS-based approach is presented for monolithic, batch-fabrication of multiple-degree-of-freedom (MDOF) IPMC actuators

that are capable of complex deformation. Such an actuator consists of multiple, individually controlled IPMC regions that are mechanically coupled through compliant, passive regions.

The developed fabrication process involves plasma etching, ion-exchange, lithography, physical vapor deposition (PVD), and electroless plating steps. Reactive ion etching (RIE) with oxygen and argon plasmas is used to selectively thin down the passive area of Nafion membrane with a patterned aluminum mask. An ion-exchange process is introduced to stiffen the Nafion. We have discovered that impregnating Nafion with platinum ions through ion-exchange can also increase its stiffness, and reduce its swellability in water and in acetone. This has proven critical in successful photolithography-based patterning in that it ensures good adhesion of photoresist to the Nafion film. A positive photoresist, AZ 9260, is used in photolithography to create thick patterns which are used as the mask in the electroless plating process to selectively grow platinum electrodes in IPMC regions.

A characterization system consisting of a CCD camera and image processing software has been set up to quantify the deformations generated by the fabricated samples. We have verified that, by controlling the phase differences between the voltage signals applied to the IPMC regions, the samples can produce sophisticated deformation modes, including bending, twisting, and cupping, which show the promise of the fabricated MDOF actuators in robotic fish and many other applications.

7642-31, Session 7a

Effects of anisotropic surface texture on the performance of ionic polymer-metal composite

Q. He, H. Ding, M. Yu, D. Guo, Z. Dai, Nanjing Univ. of Aeronautics and Astronautics (China)

Ionic polymer metal composite (IPMC), as one of the electrically activated polymers (EAP), has been widely used as artificial actuator because the advantages of large deformation, low driving voltage, low noise, lightweight and flexibility. However, relative lower output-force than that generated by other smart materials limit the wide applications of IPMC. Here we report our studies of the effects of surface texturing on the performance of IPMC. The Nafion membrane was prepared by casting of liquid solution, and then was roughed through sandblasting and polishing procedure, resulting in isotropic and anisotropic surface texture respectively. The microstructure of the polymer surface and metal electrode were analyzed and compared. Effects of the surface texture on the displacement and the output force were experimentally studied under various voltages and frequencies. Results showed that the output force of the IPMC with anisotropic surface roughening is clearly higher than that of IPMC with isotropic surface. The output force generated by IPMC with anisotropic surface could be up to 65mN, which was 3 times higher than that generated by IPMC with isotropic surface and the force is enough for the driving of artificial gecko toes. The study show that the anisotropic surface texture is an effective method to improve the performance of IPMC.

7642-32, Session 7a

Considerations for contractile electroactive polymeric materials and actuators

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Ras Labs produces electroactive polymer (EAP) based materials and actuators that bend, swell, ripple and now contract (new development) with low electric input. In addition, Ras Labs can produce EAP materials that quickly contract and then expand, repeatedly, by reversing the polarity of the electric input. These recent developments are important attributes in the field of electroactivity because of the ability of contraction and contraction-expansion to produce biomimetic motion. The mechanism of contraction is not well understood. Radionuclide-labeled experiments were conducted to follow the movement of electrolytes and water in these contractile EAPs when activated. One of the biggest challenges in developing these actuators was the electrode-EAP interface because of the pronounced movement of the EAP. Plasma treatments of metal electrodes significantly improved the attachment of the embedded electrodes to the EAP material, which allowed for the embedded electrodes and the EAP material of the actuator to work and move as a unit.

7642-33, Session 7b

Asymptotically accurate non-linear analysis of electro-elastomer structures

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Electroactive materials exhibit mechanical deformation in the presence of an electric field. This group of materials includes polymer gels, piezoelectrics, electrostrictives, dielectric elastomers, and others. They find potential applications as actuators and sensors. The current study is carried out for a special class of elastomer polymer membrane under structural applications wherein the maximum strains are of the order of 30%. Electro-elastomers respond quickly and efficiently at moderate strains. They also offer considerable actuation pressures and high specific energy densities. Applications include micro-robots, sound generators, displays, artificial blood pumps, prosthetic devices, endoscopic surgery, adaptive structures, valves, inflatable structures. The focus of this work is on the development of asymptotically accurate nonlinear theory for electro-elastomer-based membrane structures. The problem is both geometrically and materially nonlinear. The geometric nonlinearity is handled by allowing for finite deformations and the material nonlinearity is incorporated through hyperelastic material model. Electrical effect is derived through Maxwell-Faraday electrostatics. The development, based on the Variational Asymptotic Method (VAM) first proposed by Berdichevskii [1979], with moderate strains and very small thickness-to-wavelength ratio as small parameters, begins with three-dimensional nonlinear electro-elasticity and mathematically splits the analysis into a one-dimensional through-the-thickness analysis and a two-dimensional membrane analysis. The through-the-thickness analysis provides warping functions, constitutive relation between the generalized two dimensional strain and stress tensors and the electric field for the membrane analysis and a set of recovery relations to approximately express the three-dimensional mechanical fields (displacement, strain and stress) and electrical field in terms of two-dimensional variables determined from solving the equations of the membrane analysis. VAM can be implemented analytically or numerically, depending on the complexity. Thus VAM enables one to analyze the variational problem in a mathematically rigorous and yet computationally efficient manner without making any ad-hoc assumptions. Electroactive elastomers consist of nonlinear elastic, electroactive material coated on either side by compliant electrodes. On applying sufficient voltage across these electrodes, the material becomes polarized with microscopic dipoles distributed throughout the body. In this way, the material responds to the external electric field with an induced electric field opposing the external field. Energy is stored in this induced field and interacts with the mechanical energy such that the total energy is minimized when the system is in equilibrium. The ‘stress’ developed in the material due to the induced field is called the Maxwell stress. To simplify the analysis and provide certain insights, mechanical and electric effects were studied independently first, then they were rigorously coupled. Hence, this work consists of three broad sections. First section deals with the nonlinear mechanical response (in-plane and out-of-plane deformation) of hyperelastic membrane structures under mechanical loads. Dimensionally reduced effective material properties are obtained. Second section deals with response under the electric field and effective dielectric coefficients are obtained. Third section deals with the fully coupled analysis of electro-elastomers and effective piezoelectric coefficients are obtained as a function of the piezoelectric coefficients of the membrane variables. The analytical results obtained are then used to study the actuation of inflatable structures made of electro-elastomers and to predict their response under simultaneous dynamic electric and mechanical force fields.

7642-34, Session 7b

Modeling approaches for electroactive polymers

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EAP materials respond to external electrical stimulation with high deformations and can therefore outperform other smart materials in some applications. They can be used to design actuators which are capable of much higher displacements, e.g. compared to piezoelectric actuators. They can also be utilized to build generators for energy harvesting applications. Imposing large deformations will lead to great changes in capacitance, which can be exploited to convert mechanical to electrical energy with appropriate switching circuits.

However, up to now applications based on electroactive polymers have hardly ever exceeded laboratory scale; nevertheless the potential for these materials is enormous. In order to properly design and optimize robust and efficient systems reliable models are required. There are many different physical effects that need to be taken into account like the nonlinear coupling between mechanics and electrics, the nonlinear material behavior at large deformations and some time-varying effects, only to name a few. Nonetheless, up to now there have been only a few works about modeling of dielectric elastomers. Therefore a finite element model with multiphysical elements is developed and presented in this paper. It can give helpful instructions for the design and fabrication process of EAP-systems. The model can also be reduced in order to implement it in larger models for the simulation of the overall active system.

7642-35, Session 7b

Evaluation of electrostriction in dielectric elastomer actuation and instability

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This paper presents the study of the electro-stress, especially the electrostriction, in dielectric elastomer (DE) undergoing voltage-induced large deformation.

The electrostriction is investigated and evaluated by the free energy model when the dielectric permittivity did not remain constant in DE actuation. Unlike previous research on the parallel capacitor dielectric subject to voltage of 1-2V with a broad frequency band, in this paper, we study the situation when DE dielectric constant is strongly affected at different expansion levels when a high constant voltage is applied. The electrostrictive coefficients are obtained from experimental data collected in dielectric constant measurement under 3kV DC voltage. By using General Hook law, we study the relation of electric fields and the DE stretch rate with/without electrostriction and the computational results fits the experimental data more accurately (improved error of 1.75% vs. 4.76%) when the electrostriction is involved. The instability in DE actuation is explored, and two different results are presented. If the electrostriction is neglected, the free energy model failed to predict the electromechanical instability, and correct prediction is verified by taking electrostrictive effect into instability consideration.

The result suggests that the electrostriction would become pronounced at DE large deformation and the electrostrictive effect should be taken into account in the study of DE actuation stretch and the control of instability.

7642-36, Session 7b

Leakage current as a predictor of failure in dielectric elastomer actuators

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Dielectric breakdown often leads to catastrophic failure in Dielectric Elastomer Actuator(s) (DEA). The resultant damage to the dielectric membrane effectively renders the DEA useless for future actuation, and in extreme cases the sudden discharge of energy during breakdown can present a serious fire risk. The breakdown strength of DEA however is heavily dependent on the presence of microscopic defects in the membrane giving its overall breakdown strength inherent variability. The practical consequence is that DEA normally have to be operated far below their maximum performance in order to achieve consistent reliability.

Predicting when DEA are about to suffer breakdown based on feedback will enable significant increases in effective DEA performance without sacrificing reliability. It has been previously suggested that changes in the leakage current can be a harbinger of dielectric breakdown. Leakage current exhibits a sharp increase during breakdown, but up to now it has not been possible to distinguish leakage current from other current flows in situ.

In this paper the relationship between electric field and leakage current is investigated for simple VHB4905-based DEA. Particular emphasis is placed on the behaviour of leakage current during breakdown conditions and its potential as part of a "pain" parameter for predicting breakdown in a timely manner. This data is used to test an enhanced version of a Pulse Width Modulation based dynamic capacitive self-sensing system for DEA based on the authors' previous work that enables leakage current to be differentiated from both charging current and the current due to a changing capacitance.

7642-37, Session 7b

Modeling of non ideal dielectric elastomer stack actuators

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To design actuators for specific applications it is necessary to describe the performance of the actuators precisely. Hence, an accurate model is essential dimensioning dielectric elastomer stack actuators.

In this paper we discuss the electrical and mechanical modeling of such multilayer systems, the measurement of model parameters and we will show a comparison between model and real actuators.

The basic simplified equation of dielectric elastomer actuators

$p=\varepsilon \cdot E^2$

describes the electrostatic pressure causing the deformation of the actuator. However, describing a stack actuator needs to consider several important conditions like the number of connected electrodes within the stack or other surrounding passive material.

We developed a model which allows concluding the number of connected layers and the resistances of the graphite electrodesafter measuring the frequency dependent impedance of the actuators. These parameters are used to describe the dynamic actuation. Hence, the actuator layout can be optimized, maximizing the electrostatic pressure for the required bandwidth. Depending on the film thickness of the dielectric layers 60% to 90% of the layers are typically connected, contacting thinner layers is obviously more challenging.

Using the extracted electrical parameters and mechanical setup of the stack the static deflection characteristics of different actuators can be predicted precisely.

The dynamic characteristics depend on the mechanical behavior of the stack and electrical parameters as well. Finally, we show the correlation of actuator layout parameters, driving voltage conditions (amplitude and frequency) and fabrication parameters of the stack, as well. Measurement data are shown validating the presented model.

7642-38, Session 7b

Dielectric elastomer bimorphs using electrolessly-deposited silver electrodes

C. Goh, G. Lau, Nanyang Technological Univ. (Singapore)

Continuous metallic thin films, which are widely used for micro-electronic circuits, are seldom used as the electrodes for dielectric elastomer actuators (DEA) because they limit the lateral strain of

elastomer. Metalized DEA is not suitable for in-plane actuation. However, in this paper, we demonstrated a multi-layered bimorph design capable of a large out-of-plane actuation stroke even though using metalized elastomeric layers. This metalized elastomer exhibits a high breakdown voltage in comparison to the elastomer with grease electrodes.

The electroless deposition method was commonly used for silvering a mirror. The same method is used here to electrolessly deposit compliant silver electrodes onto a VHB tape (F-9469 PC). This process results in a shinny and highly conductive silver film, which is 200nm thick. In general, a resistance of 10-50 ohm is measured with probes positioned at 5 mm apart. The high conductivity ensures a fast response.

A silvered DEA bimorph is made of 3 active layers of silvered VHB on a polydimethylsiloxane (PDMS) layer. The silvered VHB layer is made of a 0.13mm-thick tape, cut into a size of 20 mm x 10 mm and with a silvered area of 16 mm x 6 mm. A tip displacement of 6 mm, with a deflection angle of around 27.5°, was observed for the DEA bimorph activated at 3000V. Electrical breakdown voltage of the silvered VHB is 3500 kV, which is higher than 2000V of a VHB tape coated with silver grease. The silvered VHB layer is found to be able to self healed after the electrical breakdown.

7642-39, Session 7b

Self-priming circuit design for dielectric elastomer generators

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Dielectric Elastomer Generator(s) (DEG) are variable capacitor power generators formed by hyper-elastic dielectric materials sandwiched between flexible electrodes. Electrical energy can be produced from a stretched, charged DEG by relaxing the mechanical deformation while maintaining the amount of charge on its electrodes. This increases the distance between opposite charges and packs like-charges more densely, increasing the amount of electrical energy. The amount of energy harvested from one cycle of this process has a limited dependence on velocity, so DEG show promise for harvesting energy from environmental sources providing variable frequency mechanical deformations such as wind and ocean waves.

None of the components in a DEG system are ideal and an electrical load drains charge, so charge is lost from the system. This means that unless extra charge is periodically added to the system, the amount of charge placed on the DEG will gradually drop. Batteries or capacitor banks typically provide this, but they also have their energy depleted over time and add bulk to the system. In this paper we present a self-priming DEG system that is capable of utilizing some of the generated energy to restore charge lost from the system, so no external priming energy source is required provided there is enough mechanical energy input. This paper will discuss how the self-priming circuit works, then we present our ABAQUS FEA model, optimizing a hand pumped DEG as a case study. Finally we fabricate our optimized DEG to verify that it can self-prime and drive a load.

7642-120, Session 7b

Energy harvesting using electro active polymers

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Due to the large amount of deformation Dielectric Polymers are predestined for applications such as artificial muscles, speakers or valves. Beside of this actuator function, Electro Active Polymers (EAP) can also be used as generators to convert mechanical strain energy into electrical energy by charge transfer using the polymer's capacitive behaviour. The requirements for these so called EAP-generators as energy harvesting devices are a high dielectric break down stress (DBS) and a large change of the capacity. The relative energy gain basically depends on the capacity change, while the DBS affects the possible amount of charges on the dielectric polymer, which are the basis for an energy gain. To analyze the design of EAP-generators at first and to optimize material parameters of suitable EAP-generators afterwards, a validate simulation model regarding material properties on the one hand and geometric properties on the other hand is necessary. Further on, the simulation model is also used to optimize the Energy Harvesting Cycle. The EAP-generator used for the simulation model consists of a polymer (i.e. polyurethane) between two flexible conducting electrodes, integrated into an experimental case. For the parameterization of the EAP-generator model it is characterized in a test bench, which is designed to strain the device in one lateral direction using a linear electric motor.

7642-41, Session 8a

Nanotube yarns as high stress actuators and sensors

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The high stiffness and tensile strength of carbon nanotube yarns enables sensing and actuation at loads that are impractical in electroactive polymers. Operation at several hundred megapascals is observed, with strains of 0.6 %, and little creep. Ionic liquids are employed to minimize creep. The mechanisms of actuation and of sensing are related to the electrochemical charging of the yarns and to yarn mechanics. A model that describes the electromechanical coupling is presented. The model shows that actuation strain is related to effective ion size, and is dependent on capacitance of the nanotubes. The main fit parameter in the models is the radial modulus of the yarns, for which only crude measurements using AFM are available.

The interactions between yarn bundles are compared with those that occur in electrostatically actuated dry nanotube sheets, where strains of tens of percent or more are achieved at high frequencies. In these materials the aniosotropic modulus is critical to achieving large strains.

7642-42, Session 8a

Conductive filler morphology effect on performance of ionic polymer conductive network composite actuators

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Several generations of ionic polymer metal composite (IPMC) actuators have been developed. It has been discovered that the composite electrodes which are composed of electronic conductor fillers and ionic conductors, have great impact on performance of ionic polymer actuators by affecting strain level, efficiency and speed. One of important factors in composite electrodes is the shape of electronic conductor fillers, which includes three kinds: particles, wires and plates. RuO2 nanoparticles, vertically aligned carbon nanotube (CNT) and exfoliated graphite nano platelets are used as conductor fillers for different shapes, respectively. The rest parts in actuators are Nafion as ionomer in composite/middle layers and room temperature ionic liquid 1-ethyl-3-methylimidazolium trifluoromethanesulfonate as electrolytes. It is found that the aligned nano wires and plates show advantages over random nano-particles. By using aligned CNT array and exfoliated graphite platelets, the strain speed increases due to larger ionic conductivity; the effective capacitance is increased due to larger accessible area for ions and higher electronic conduction; the strain increase from 3% to more than 10%. Furthermore, electromechanical

efficiency is improved resulting from the anisotropic structure in aligned CNT and exfoliated graphite platelet composite. The formal one clamps strain in thickness direction and the latter one further clamps strain in width direction.

7642-43, Session 8a

Ionic liquids in ionic polymer conductor network composite actuators

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In ionic polymer actuators the accumulation or depletion of excess charges (ions) at the composite electrodes under an applied voltage will generate strain in these regions. In order to increase the charge density and population at the electrodes so that a large strain and high force output can be realized, various ionomeric polymer/conductive network composites (CNC) electrodes and electrolytes have been developed to form ionomeric polymer/CNC actuators (IPCNC). IPCNC actuators are attractive because it can be operated under a few volts. However, IPCNC actuators suffer a low actuation speed, low efficiency (<3 %), and low elastic energy density. The limiting factors of low actuation speed and efficiency come both from the morphology of composite electrodes and electrolytes. Since it is already shown that part of the causes for low ion transport speed exist in the composite electrodes of IPCNC actuator, in this study we will focus on the issues of designing and using electrolytes which are ionic liquids (ILs). The issues include ion size, activation energy, ion clusters, and etc. Comparison is done by measuring capacitance, strain level and strain rate of actuators with four ILs, plus using ab initio method to calculate ion size and different ion pair status percentage. It is shown that by correctly using combination of different cation and anion size, the speed and efficiency could be dramatically improved. In addition, we will show the preliminary results of using different ILs to couple different composite electrodes with various morphologies for best performance.

7642-44, Session 8a

Experimental investigations on carbon nanotube actuators defining the operation point and its standard deviation

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Carbon nanotube (CNT) actuators have been extensively investigated from the perspective of materials, their composition, and system construction as well as from three main performance features, which are displacement, force and reaction time. However, up till now none of CNT actuators has reached the stage of implementation into products. It is due to the fact that even though from the point of view of performance each property can reach satisfactory values, their combination is much more difficult, as they are not proportional. This relation of properties motivated the work to test and investigate currently available CNT-polymer actuators to define their operation point. Under this term one should understand a performance of actuator where displacement, force and reaction time do not affect each other. In other words, any change in one of the properties will adversely affect at least one of the remaining ones.

The measurements are performed in out-of-plane mode on 2 cm diameter samples in low frequency range (0,01 - 1 Hz) under application of low voltage (2 V).

Measurement curves of three main actuator properties are plotted together against the frequency resulting in operation point as the intersection point of those curves. Additionally the deviations in actuator performance are assessed to reflect the actuators' reproducibility and their production process stability by means of standard deviation.

Knowledge about the relation between actuator properties together with the value of operation point will allow better opposition of the existing CNT actuator against its potential applications.

7642-45, Session 8a

A study for thickness property of IPMCs based on rules

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Generally ionic polymer-metal composites (IPMCs) have been made from commercially available perfluorinated ion-exchange polymer membranes such as Nafion film. The membrane has a typical thickness in the range of about 100~300 . Commonly, the thicker membrane is used at the IPMC, the larger bending displacement could be got. However, we can predict the fact not to continually increase the displacement.

In this study, we consider the relation between the bending displacement and the thickness of the membrane through the various experiments. We will establish a model to calculate the bending displacement generated according to the change of the thickness and propose the optimized condition of the thickness.

7642-46, Session 8b

Nanoporous carbon-based electrodes for high strain ionomeric bending actuators

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Ionic polymer metal composites (IPMCs) are electroactive material devices that bend at low applied voltage (1-4 V). Inversely, a voltage is generated when the materials are deformed,which makes them useful both as sensors and actuators. In this paper, we propose two new highly porous carbon materials as electrodes for IPMC actuators, generating a high specific area, and compare their electromechanical performance with recently reported RuO2 electrodes and conventional IPMCs. Using a direct assembly process (DAP), we synthesize ionic liquid (Emi-Tf) actuators with either carbide-derived carbon (CDC) or coconut-shell-based activated carbon-based electrodes. The carbon electrodes were applied onto ionic liquid-swollen Nafion membranes using a direct assembly process. The study demonstrates that actuators based on carbon electrodes derived from TiC have the greatest peak-to-peak strain output, reaching up to 20.4 mε (equivalent to >2%) at a 2 V actuation signal, exceeding that of the RuO2 electrodes by more than 100%. The electrodes synthesized from TiC-derived carbon also exhibit significantly higher maximum strain rate. The differences between the materials are discussed in terms of molecular interactions and mechanisms upon actuation in the different electrodes.

7642-47, Session 8b

Dielectric elastomer actuators of silicone rubber-titania composites obtained by dielectrophoretic assembly of filler particles

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High dielectric permittivity and low loss factor are desirable for dielectric elastomer actuators to reduce the required electric voltage. Structured Polymer composites may serve this purpose. Formation of controlled morphology of fillers in polymeric composites may be difficult to achieve by conventional methods such as mechanical shear or chemical methods. Tunable structure of filler and anisotropic properties in composites can be obtained by exploiting dielectrophoretic assembly of fillers in a polymer composite by using electric fields. In this study, different concentrations of TiO2 (Titania) particles in silicone rubber matrix were assembled in a chain-like structure by using an alternating electric field. Silicone rubber matrix was vulcanized to transform the liquid to solid and maintain the filler structure in the desired direction. Generation of chain structure of filler

was verified by Scanning Electron Microscopy (SEM) and equilibrium swelling. It was shown that dielectric permittivity of the oriented composite is higher whereas its dielectric loss is lower in the orientation (thickness) direction than those for the composites with random distribution of filler. A critical concentration of filler was distinguished as the percolation point at which the change in dielectric behavior is exaggerated. The desired dielectric properties were achieved by orienting filler in the thickness direction. Effect of filler structure on enhancement of actuation force was quantified using an in-house actuation set-up.

7642-48, Session 8b

NOMS: nano opto-mechanical systems

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Nano-opto mechanical Systems (NOMS) based on the photoactuation of optoactive polymer actuators and devices (OAPAD) is a much sought-after technology. In this scheme, light sources promote mechanical actuation of polymeric materials producing a variety of nano-opto mechanical systems such as nano-grippers. The European Union NOMS consortium is a multidisciplinary team assembled to build a tactile tablet for the visually-impaired. The consortium is formed by experts in materials, optics, microsystems, neuropsychology, as well as end users, and commercial partners who will fabricate the first visual aid tablet based on photoactuation technology.

The purpose of this paper is to stir an interest in the field of photoactuators; promoting OAPAD to mainstream R&D. To this purpose, we will review the current state of the art on photoactuators and address outstanding concerns towards microsystem integration. Photoactive actuators could be a complement to Electroactive Polymer Actuators and Devices (EAPAD). Indeed, the “wireless” character of optical actuation could pose an advantage to electrical actuation in some environments. Albeit, given the similarities of smart materials presenting electro- and photo-actuation, advancements of photactuators in microsystem integration are likely to produce synergistic advancements in the integration of electroactuators and vice versa. Ground-breaking OAPAD lay the ground of an incipient field, likely to generate a strong impact in a variety of scientific arenas. Ultimately, we envision optical actuation in multiple environments such as intracellular motors, artificial muscles, and tactile displays for the general public.

7642-49, Session 8b

Self-assembled regular arrays of carbon nanotube and the route toward actuation of shape memory polymer

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The synthesis of massive arrays of monodispersed carbon nanotubes that are self-assembled on hydrophilic polycarbonate membrane is reported. This approach involves individual carbon nanotube manufacturing by non-ionic surfactant to aid in dispersion and nanotubes self-assembled for three-dimensional orientation by high press filtration. The inherent capability of carbon nanotube and microstructure of well-packed arrays predominate excellent conductive properties of massive arrays. These potential applications of nanometer-sized sensor, probe and energy resistor have been characterized in this study. Furthermore, the route toward application of self-assembled regular arrays, as heat transmission intermedium, has been carried out by activating shape-memory polymer. The electrical conductivity of insulating polymer is significantly improved by assembled carbon nanotubes, resulting in shape recovery behavior of nanocomposite being driven by electrical resistive heating.

7642-50, Session 8b

Thermomechanical properties of multiwalled carbon nanotube reinforced shape-memory polymer nanocomposite

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In the present study, multiwalled carbon nanotubes (MWCNTs) reinforced shape memory polymer (SMP) nanocomposites were prepared with a high shear mixing process. The shape memory effects, thermomechanical properties and electrical behaviors were characterized to demonstrate the effect of the incorporation of the MWCNTs. A well dispersion of the MWCNTs in the SMP were reached with the current mixing process and brought in enhanced mechanical properties, especially the modulus. The shape fixity and shape memory recovery ratio can reach more than 98% for both plain SMP and nanocomposites. The transition temperature for the shape memory of the nanocomposites does not vary with the MWCNT content, while the shape memory recovery rate decreases with the MWCNTs up to 2 wt.%. The testing on the repeatability and durability of the shape memory effect indicates that the nanocomposites possess the same shape memory effects as the plain SMP over 5 consecutive shape memory cycles. In the transition temperature range, the addition of the MWCNTs enhances the modulus of the SMP significantly, indicating the increased recovery force. With the enhanced electrical conductivity of the nanocomposite due to the incorporation of MWCNTs, the electro-active shape memory of the nanocomposites is realized.

7642-51, Session 8b

The constitutive relation of silicone rubber soft active materials

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Silicone rubber is a common dielectric elastomer material. Actuators made from it show excellent activate properties including very large strains (up to 380%), high elastic energy densities (up to 3.4 J/g), high efficiency, high responsive speed, good reliability and durability, etc. When voltage is applied on the compliant electrodes of the dielectric elastomers silicone rubber, the polymer shrinks along the electric field and expands in the transverse plane. In this paper, a theoretical analysis is performed on the coupling effects of the mechanical and electric fields. A nonlinear field theory of deformable dielectrics and hyperelastic theory are adopted to analyze the electromechanical field behavior of these actuators. Also the mechanical behavior of the dielectric elastomer silicone rubber undergoing large free deformation is studied. Finally, the constitutive model of a dielectric elastomer silicone rubber composite under free deformation and restrained deformation is derived.

7642-52, Session 9a

Multi-scale mechanical modeling of composite electroactive polymer tubular actuators

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Danfoss Polypower has developed a type of DEAP material that combines a polymer thin film with a special compliant metal electrode design that provides unidirectional motion. Based on this, a core-free tubular actuator has been developed by rolling the DEAP thin film. There are passive areas of material at both ends of the actuator. These provide an area to attach the electrode connections and end caps as well as stopping any short circuits along the edges.

The modeling of such systems are challenging due to their multi-scale and multi-physics nature. In this work we focus on the multi-scale part of the modeling problem only taking into account the electrostatic part by including the Maxwell pressure.

Due to the multi-scale nature of the problem it is computationally

too expensive to directly implement the full three-dimensional (3D) problem (Navier's equations). This difficulty is overcome by reducing the 3D model to two two-dimensional (2D) models easily handled within the finite element framework. The passive areas degrade the force characteristics of the actuator. This is taken into account by considering the passive areas as springs. The models are compared with experimental data obtained from a Danfoss PolyPower 'InLastor' actuator. We show that by taking into account the passive areas we get good agreement between the model and the experiments, this not being the case for a model which only takes into account the active area.

7642-53, Session 9a

Three-dimensional numerical implementation of a thermoelastic, finite deformation constitutive model for shape memory polymers

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Shape memory polymers (SMPs) are a class of active materials that, under an appropriate thermomechanical cycle, will recover a thermodynamically stable applied strain. SMPs have been the focus of many recent experimental and theoretical investigations, many of which consider the SMP response due to infinitesimal deformations. This paper focuses on the three-dimensional implementation of a finite deformation constitutive model. The previously developed model is based on the theory of nonlinear thermoelasticity, and accounts for the coexisting active and frozen phases of the SMPs as well as the transition between the two phases. The model is implemented as a user material subroutine (UMAT) in ABAQUS.

Upon implementing the model, the material properties in the model are calibrated from finite deformation experimental data of polyurethane (PU) SMPs. Tensile tests are performed on the PU specimens for both constant strain and constant stress recovery scenarios. After calibrating from a subset of the experimental results, the model is used to predict the material response for the other thermomechanical load paths. Furthermore, the three-dimensional implementation allows for the modeling of complex geometries. Geometries of interest are based on applications that include cardiovascular stents and hybrid SMA-SMP joints and composites.

7642-54, Session 9a

A model of the nonlinear capacitance and electrochemical behavior of ionic liquid-ionic polymer transducers

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Ionic liquid-ionic polymer transducers (IL-IPTs) have received increasing attention in recent years due to advantages over their water-based counterparts. The negligible vapor pressure of an ionic liquid allows for the transducer to operate in free air, opening up a wide range of possible applications. In this work, a model of the electrochemical behavior of IL-IPTs is proposed which accounts for the multiple mobile ionic species in these devices and the nonlinearities due to the large sizes of the ionic liquid ions and non-symmetry of the equilibrium charge distribution. A numerical solution to the system of governing PDE's is obtained using the finite element method and the results are used to describe the nonlinear capacitance of an IL-IPT. In recent work, Kornyshev has shown that the electrochemical behavior of a neat ionic liquid is distinctly different from a typical electrolyte solution. Specifically, the double layer capacitance decreases with the magnitude of the applied voltage. Here, it is shown that the capacitance of an IL-IPT reaches a maximum at zero applied voltage and then drops sharply as the applied voltage increases. Experimental measurements of the capacitance/voltage relation of an IPT are taken and a comparison is made with the proposed theory. The decrease in capacitance with the applied voltage has a detrimental effect on actuation and this effect should be minimized in order to achieve optimum performance. The results of the proposed electrochemical model are discussed in relation to the actuation mechanisms in an IPT and suggestions are made for new transducers.

7642-55, Session 9a

Optimal clamping conditions for linear strain terpolymer actuators

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A recent study has been conducted using planar linear strain multilayer electrostrictive P(VDF-TrFE) terpolymer actuators to optimize the levels of strain achievable using a given actuator under various voltage excitations. Clamping over a reduced section of the actuator's width is essential for devices that have aspect ratios (length to width) which are small, as the outer un-electroded margin of the actuator produces a clamping effect. It has been found that significant increases in both the strain and the amount of force generated by the actuator can be achieved by clamping over a fraction of the actuator's width along the top and bottom of the actuator. This phenomenon is explained using a simple beam spring model to characterize device behavior numerically and to provide a model for comparison to experimental results. Experimental results presented verify the appropriateness of the simple model and demonstrate the effectiveness of a reduced boundary condition.

7642-56, Session 9a

Thermo-chemo-electro-mechanical modeling of polyelectrolyte gels

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Polyelectrolyte gels show adaptive viscoelastic characteristics. In water based solutions they have enormous swelling capabilities under the influence of different possible stimulation types, such as chemical, electrical or thermal stimulation.

In the present work a fully coupled 3-field formulation for polyelectrolyte gels using the Finite Element Method (FEM) is applied. This formulation consists of a chemical, electrical,

and mechanical field equation. The mechanical field is coupled to the chemo-electrical field by a prescribed strain stemming from an osmotic pressure term. In experiments it has been proven that there is a large dependency between the applied temperature and the actual swelling degree of the gel. In the present research, the thermal stimulation is investigated. First, only the actual temperature is considered in the osmotic pressure term. Second,

additionally, temperature-dependant material parameters obtained from experimental measurements are applied. The calibration of the derived simulation results is performed with experimental results available in literature.

7642-57, Session 9a

Electro-mechanical modeling of interpenetrating polymer network reinforced acrylic elastomer

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Interpenetrating polymer network reinforced acrylic elastomer (IPN) is a very promising new material for dielectric elastomer actuators. IPN achieves the performance of pre-strained acrylic elastomers without

the need of pre-strain. Thus it allows the design of free-standing contractile dielectric actuators featuring very high actuation forces and excellent reliability. This work presents the electro-mechanical characterization of an acrylic IPN elastomer. We determined a time-dependent 3D large strain model that is suitable for finite element simulation of IPN actuators of general design. In order to characterize the mechanical behavior of IPN an extensive experimental campaign was carried out involving uniaxial and equibiaxial tension, relaxation as well as membrane inflation experiments. Using image based local deformation measurements as well as iterative finite element calculations we determined constitutive model parameters that describe the mechanical response for a wide range of strain and strain rate. Our experimental observations reveal an important influence of the material composition on mechanical behaviour. We propose a new approach to rationalize the observed material composition dependence and consider it in the model formulation. This modified model is shown to provide an excellent fit of the multiaxial response of different IPN membranes. The dielectric permittivity of IPN was characterized for a range of biaxial strain states, and shown to decrease with increasing planar strain. For electro-mechanical coupling, our model uses the equation of Pelrine et al. modified by a strain dependent permittivity. The predictive capabilities of the electromechanical model are demonstrated based on observations from pre-strained circular actuators.

7642-58, Session 9a

A theoretical modeling of mechanical and electrical properties of enhanced dielectric elastomers

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In this paper, a theoretical model is derived to describe the effects of additive on the electromechanical properties of dielectric elastomers (DE). Additives such as silicone and copolymers have been infused into a DE material such as 3M VHB 4910 resulting in improved electromechanical properties. However, due to the challenges experienced in tuning material properties for optimized actuation and sensing response in a laboratory, a theoretical model that predicts bulk properties of two phase materials would be of utmost value in pursuing experimental outcomes in a systematic way.

A DE with an additive is considered as a heterogeneous material consisting of two phases, a base matrix and inclusions, respectively. Within a micromechanics framework, a multiple-inclusion method (Eshelby or Mori-Tanaka) are used to determine the bulk properties of the resultant material. In the first approach, it is assumed that all the inclusions are geometrically identical and interactions between them are neglected. The volume fraction and geometry of an additive are used to compute the material properties. This approach is limited to the case of low volume concentrations of the additive. For higher additive concentrations, the second approach considers interactions between the constituents so that it includes the effect of the surrounding matrix and the other inclusion.

In this paper, an enhanced DE is modeled using VHB 4905 with additive. Theoretical calculations describing the effect of additives on the electromechanical properties of DEs are presented. It is expected that the theoretical model will provide guidelines for tuning the material properties of DE.

7642-59, Session 9b

Training of artificial muscles based on conducting polymers

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We demonstrate first time that artificial muscles based on conducting polymers, polyaniline films can be strengthened in the electrochemomechanical strain (ECMS) upon training. It has been found in fact that the stroke of ECMS of polyaniline films increased to 6.5% by training from that of initial strain of 4.8% before applying high tensile stress, accompanying the creeping. The creeping or anisotropic strain is induced by uniaxial stretching and/or slipping of polymer chains along the stretch direction (partially due to breaking of polymer chains). By release of the high tensile stress, the anisotropic strain is relaxed to the original form by electrochemical cycling due to the thermal fluctuation of polymer chains or elasticity. Namely the training effect is essentially based on the electrochemical cycling under high tensile stress, followed by release of the tensile stress. It will also be mentioned that the training effects are also obtained in electrodeposited polypyrrole film. The training effect of Polyaniline is more pronounced than the case of polypyrrole. Detailed experimental facts and the mechanisms will be reported.

7642-60, Session 9b

DNA hydrogel for bioinspired actuators

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DNA hydrogels have a wide range of biomedical applications in tissue engineering and drug delivery systems. There are two ways to create DNA hydrogel structures: one is enzyme-catalyzed assembly of synthetic DNA and the other is by crosslinking natural DNA chemically. Here, we report a DNA hydrogel fiber without chemical crosslinking or other gelling agents. A DNA hydrogel fiber without any covalent crosslinks that is composed of knotted entanglements of DNA flexible strands has been prepared using a wet spinning method employing an ionic liquid as the DNA condensing agent and coagulation solvent. The DNA fiber maintained a hydrogel form for about 3 months after soaking in deionized water and a high swelling ratio of over 600% compared to the dry state. The DNA hydrogel fibers may be exploited in a variety of biomedical applications such as biocompatible composites, sensors and artificial muscles.

7642-61, Session 9b

Optimisation of bio-inspired multi-segment IPMC cilia

S. Sareh, A. T. Conn, J. M. Rossiter, Univ. of Bristol (United Kingdom)

In nature, unidirectional fluid flows are often induced at micro-scales by cilia and related organelles. A controllable unidirectional flow is beneficial at these scales for a range of novel robotic and medical applications, whether the flow is used for propulsion (e.g. swimming robots) or mass transfer (e.g. prosthetic trachea). Ionic Polymer Metal Composites (IPMCs) are innovative smart materials that can be used directly as active propulsive surfaces rather than a traditional motor and propeller. IPMC actuators with two segmented electrodes that attempt to mimic the motion of cilia-like organelles have been realised. In this paper the optimisation of these actuators towards producing unidirectional flows is described.

A parametric study of the kinematic and hydrodynamic effect of modulating the drive signal has been conducted. As with eukaryotic cilia and flagella found in mammals, the segmented IPMC actuator can generate both flexural (asymmetric) and undulatory (symmetric) motions from the same physical structure. The motion is controlled by applying profiles of driving frequencies and phase differences. Kinematic analysis using a camera and laser displacement sensor has been used to measure and classify different motion types. The hydrodynamic forces produced by each motion type have been estimated using particle-tracking flow visualisation. This allows drive signal profiles to be ranked in terms of the actuator power output and fluid flow directionality. Using the results of the parametric study, the IPMC motion is optimised towards producing unidirectional flow via a repeatable, asymmetric cilia motion. Finally, the hydrodynamic effects of scaling are discussed for cilia-like IPMC actuators.

7642-62, Session 9b

Mechanical characterization of conducting polymer actuated neural probes under physiological settings

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Most implantable chronic neural probes have fixed electrode sites on the shank of the probe. Neural probe shapes and insertion methods have been shown to have considerable effects on the resulting chronic reactive tissue response that encapsulates probes. We are developing probes with controllable articulated electrode projections, which are expected to provoke less reactive tissue response due to the projections being minimally sized, as well as to permit a degree of independence from the probe shank allowing the recording sites to "float" within the brain. The objective of this study was to predict and analyze the force-generating capability of conducting polymer bilayer actuators to actuate electrode projections from the probe shank under physiological settings.

Custom parylene beams 1 cm long having varying widths (100 - 1000 microns) and thicknesses (8 - 15 microns) were coated with Cr/Au. Polypyrrole was potentiostatically polymerized onto the Au at 0.5 V in a solution of 0.1 M pyrrole and 0.1 M dodecylbenzenesulfonate (DBS) to varying thicknesses. Using cyclic voltammetry, the bilayer beams were cycled between 0 and -1 V in artificial cerebral spinal fluid at 37C, as well as in aqueous NaDBS at room temperature as a control. Video and scanning electron micrographs were taken and used to quantify thicknesses and deflections. Force and strain were measured. By integrating polypyrrole-based conducting polymer actuators, we present a novel microfabricated neural electrode. We demonstrate that by oxidizing and reducing the polymer layer, we can control electrode projection deflection under physiological settings.

7642-63, Session 9b

Robust PID force control of IPMC actuators

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Compared with the conventional actuators, the response of the IPMC can be easily changed by environmental conditions such as humidity or counter ions within the polymer. Therefore, the precise force control of IPMCs is a challenging task and it is expected that the development of robust or adaptive compensation methods for the uncertainty or the variation of the model. From the point of view of a practical use, PID (proportional, integral and derivative) control is the most commonly used methods due to the simplicity. However, the performance may degrade easily owing to the uncertainty, or the system may become unstable, unless the PID gains are properly designed.

This paper discusses a simple robust PID tuning method for the force control of IPMC actuators. As the first step, the system is modeled by a linear time invariant system which represents the responses of the electrical and the electro-mechanical systems.

The uncertainty is expressed by interval polynomials of the closed-loop characteristic equation. The intervals of the uncertainty are determined by an identification experiment. As the second step, the PID gain is determined by a pole assignment to be satisfied the robust stability. Using Kharitonov's theorem, we show that only one polynomial is required for the robust stability check of the model.

In the experimental verification, two IPMCs are used for the control and the disturbance. The step response and the tracking control for the sinusoidal input are examined with and without the disturbance. Experimental results show the effectiveness of the force control achieved by the proposed method.

7642-64, Session 9b

Fabrication of multiwalled carbon nanotube polydimethylsiloxne nanocomposite polymer flexible microelectrodes for microfluidics and MEMS

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Over a last decade Polydimethylsiloxane (PDMS) has been the first choice by researchers worldwide for rapid prototyping of lab on a chip systems (LOC's) because of its unique properties such as, it can be easily micromolded and is an insulator, transparent, flexible and biocompatible. One of the drawbacks of PDMS based LOC's is that, it is difficult to embed, pattern or integrate conductive tracks on PDMS to because the adhesion between metals (eg. Gold, Silver, Platnium etc.), intrinsically conducting polymers (eg. PDOT:PSS) and PDMS is very week and often leads to micro-cracks resulting in failure of device. The integration of conductive tracks or structures in PDMS based LOC's is extremely important for signal routing, interfacing to signal processing electronics, and to power active devices. Hence there is need to develop flexible electrically conducting polymer which not only have a good adhesion to PDMS but is also are resistant to micro-crack formation. The work improves on previous research in which Multiwalled carbon nanotubes were manually mixed in PDMS matrix and then ultrasonically agitated in agitated ultrasonically at 24 khz. In this work we have employed shear mixing technique to sdisperse MWCNT's in PDMS matrix and for the first time present fabrication of microelectrodes using our materials and processes. Multiwalled Carbon Nanotubes with an outer diameter of 10nm and length of 30μm were purchased from Cheap Tubes Inc, USA) and PDMS polymer matrix which consists of base elastomer and curing agent (Sylgard 184 Elastomer Kit) was bought from Dow Corning, USA. The electrically MWCNT -PDMS nanocomposite is prepared by shear mixing. The resultant nanocomposite was successfully micromolded against a SU-8 master mold in to electrodes of 1000 μm x 100 μm with a height of 50 μm in size on a non conducting PDMS. The electrical resistivity of the electrodes was calculated using four probe measurement and was found to be equal to 89.2 at 2 weight percentage of MWCNT in PDMS Matrix which is better than our previously reported value of 102.12 Ω/ cm at similar weight percentage.

7642-87, Session 9b

Anthropomorphic robotic face with servo-driven muscle system: a comparative analysis with EAP systems

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An expressive robotic face with muscle locations based on spatial point tracking of a human face has been developed. Servo motors mounted within the skull pull anchor wires that were attached on the inside of a silicone skin that forms the outer face layer. The deformation of the skin allows the face to display expressions. The basic expressions required to aid normal conversations can be conveyed by this current generation prototype. The skin possesses material properties very similar to that of human skin and contributes to bio-mimetic appearance and functionality. A two degree of freedom (DOF) set of eyes with pinhole cameras mounted inside the head capable of blinking and pupil dilation was also developed. The eyes can also be used for visual feedback. We analyze the performance of the face using mathematical models and compare the expressions achieved with that of a human face. This research is being done with the aim to increase the quality of training for medical students by simulating patient facial expression under different medical situations. This paper will address the advantages and disadvantages of the prototype with respect to electro-active polymer based actuation in terms of motion, power consumption, precision and control.

Conf. 7642: Electroactive Polymer Actuators and Devices (EAPAD) XII

7642-66, Session 10a

Dielectric electro active polymers: development of an industry

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Dielectric electro active polymers hold much promise as a smart material. Over the years devices have been developed that demonstrate DEAP's unique capabilities as an actuator, sensor, and energy conversion. In recent years significant progress has been made towards commercialization of this technology platform. The behaviour of these devices has been widely modelled and models correlated to real world devices. A wide network of international researchers continues to extend the state of the art and equip engineers with the skills and background to design DEAP into numerous applications. A strong collaborative environment exists between research and industry, consortia like organizations are being formed to maximize research. DEAP is poised for an era of rapid acceleration of capabilities and acceptance into mainstream products.

7642-67, Session 10a

A hybrid microbial dielectric elastomer generator for autonomous robots

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Dielectric elastomer generator (DEG) systems use elastomer membranes coated with compliant electrodes. Energy can be harvested when work is done on a DEG membrane through coupling between mechanical strain actuated by an external source such as wind and electrical charge: 1) wind deforms the membrane, 2) a bias voltage charges the membrane, 3) the membrane is relaxed raising the potential energy per charge, and 4) charge is drained to an electrical load or storage capacitor. The system requires starting charge and charge to compensate for losses due to leakage.

A self-primer circuit can restore the leaked charge and the starting charge can be supplied by another energy source such as microbes. Consider the Ecobot robot that converts biomass, in the form of flies, to electrical energy using microbial fuel cells (MFC). We have used the Ecobot MFC system to supply starting charge at between 3 and 5 volts to a DEG coupled to a self-primer circuit. The DEG membrane was cyclically stretched producing charge that replenished leakage losses and supplied excess charge for Ecobot's storage capacitors.

Combining MFCs with DEGs has many advantages. The robot could maintain energy stores should there be a temporary reduction in the biomass intake or wind loading. There is no need for a heavy auxiliary battery. The DEG activation can be controlled by a central processor, and turned off when the wind stops. Finally, the high voltage charges used in the DEG can also be used for trapping flies, thus assisting in replenishing the MFC.

7642-68, Session 10b

Feedback control of BISMAC actuators through active temperature sensing

A. Villanueva, S. Priya, Virginia Polytechnic Institute and State Univ. (United States)

Bio-inspired shape memory alloy composite (BISMAC) actuators have been developed for the propulsion system of unmanned undersea vehicles (UUVs) mimicking the rowing mechanism utilized by jellyfish with small fineness ratio. BISMAC actuators consisting of silicone, spring steel and shape memory allow wires were shown to recreate the bell deformation of Aurelia aurita jellyfish species. However, in order to achieve a similar cycle time as the natural counterpart, it is important to incorporate active temperature control. Initial tests were conducted to experimentally determine the temperature distribution along the actuator in air and aqueous conditions. Analytical and finite element heat transfer models were developed to compare with experimental results. The models allowed optimization of actuator structure in terms of energy efficiency by predicting the effect of design parameters such as silicone thickness and SMA wire diameter. A feedback control system was implemented by sensing temperature at the surface of the SMA wires in order to match the Aurelia aurita cycle time and therefore maximize propulsion efficiency. Current feedback control allows the optimization of SMA power consumption and prevents their overheating for a better actuation lifespan.

7642-69, Session 10b

Biomimetic control for DEA arrays

B. M. O'Brien, T. A. Gisby, S. Q. Xie, The Univ. of Auckland (New Zealand); E. P. Calius, Industrial Research Ltd. (New Zealand); I. A. Anderson, The Univ. of Auckland (New Zealand)

Arrays of actuators utilizing mechano-sensitive control strategies are ubiquitous in nature across a variety of size scales. An example is the Comb Jelly, whose longitudinal rows of ciliated paddles are controlled in this manner, with each paddle triggering the next to generate a wave of actuation that sweeps down the row. In a similar fashion, the beating of the human heart is regulated by mechano-sensitive feedback loops occurring from the cellular to whole organ level.

This control strategy is particularly powerful when used in Dielectric Elastomer Actuator(s) (DEA) systems, as DEA can be rendered self-sensing and readily fabricated into arrays that are useful for a variety of applications. Self-sensing feedback provides mechanical state information that can be used to detect when a DEA is influenced by one of its neighbors. We have previously shown that an array of DEA bending actuators can be controlled to produce a wave of actuation using a simple self-sensing state machine for each unit of the array.

In this paper we show how the speed of this wave can be controlled using multi-level biomimetic controllers. The controllers manipulate global state machine variables such as sensitivity, charging or discharging current and refractory period to regulate the speed of the wave. The performance of different controllers was evaluated experimentally by applying them to real DEA arrays.

It is expected that such controllers will have multiple applications in robotics. Several applications, including flexible robotic hearts, peristaltic pumps, conveyor systems, and propulsion systems will be discussed.

7642-70, Session 10b

Control of twisting motion of a multi-electrode IPMC actuator

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A novel multi-electrode ionic polymer-metal composite (IPMC) actuator is proposed for applications requiring multiple degrees-of-freedom motion, such as bending and twisting, for applications that include highly-dexterous artificial fins for underwater systems and artificial valves in biomedical devices. The multi-electrode pattern on the IPMC is created using two techniques, masking and surface machining. The twisting ability of a prototype actuator is evaluated and compared to an electro-mechanical model developed using the finite element method. The model is developed for optimizing the electrode pattern for maximizing actuation performance, such as twisting motion. A digital control system is proposed to control the multiple-electrodes on the IPMC actuator to achieve bending and twisting motion. Experimental results show achievable twisting up to 5 degrees for a 25 mm x 50 mm x 0.2 mm actuator. Technical design challenges and performance limitations are discussed.

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7642-71, Session 11a

Polypyrrole composite actuator synthesis, characterization, and application for Jellyfish unmanned underwater vehicle and robotic face

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In this paper, we analyze the effect of geometry in conductive polymer-metal composite actuators. The stripe actuator design consists of gold coated polyvinylidene difluoride (PVDF) substrate membrane with polypyrrole film grown potentiodynamically on top and bottom in sandwich structure. For axial type actuator, a sacrificial core substrate was used which can be dissolved after polymerization of Pyrrole. Synthesis of all samples was done using cyclic voltametry technique. Result indicate that axial type actuator consisting of 0.25 M Pyrrole, 0.10 M TBAP and 0.5 M KCl in aqueous solution exhibits strain up to 6 % for applied potential of 6V DC after 80 sec stimulation time and exhibits18 kPa blocking stress. Characterization of the actuator was conducted to establish stress-strain and energy density - time response relationships. Potential applications of conductive polymer based actuator include biometric jellyfish and facial expressive robotic head.

7642-72, Session 11a

Large planar dielectric elastomer actuators for fish-like propulsion of an airship

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One of the great advantages of dielectric elastomers (DE) is their scalability. Large planar DE are quite unique in the world of actuators. An ideal application of such an actuator is the activation of inflatable struc-tures. As research platform a model airship of 8 m in length was constructed that can move its body and tail fin in a fish-like manner. Unlike the propulsion with rotors, the fish-like movement is silent and the airflow around the airship is not disturbed by the fast airflow after the rotor. The bending actuation of the helium-filled hull is realized with planar two-layered DE of 1.6 m2 on either side. The tail fin is moved by four-layer planar DE of 0.3 m2 on either side. A design for actuators of such dimensions was developed and the actua-tors were characterized in terms of performance.

7642-73, Session 11a

Dielectric elastomer actuators with zero-energy fixity

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Although dielectric elastomer actuators are becoming more powerful and more versatile one disadvantage of DEAs is the need to continuously supply electrical power in order to maintain an actuated state. Previous solutions to this problem have involved the construction of a bistable or multi-stable rigid mechanical structure or the addition of some external locking mechanism. Such structures and mechanisms add unwanted complexity and bulk. In this paper we present a dielectric elastomer actuator that exhibits zero-energy fixity. That is, the actuator can be switched into a rigid state where it requires no energy to maintain its actuated shape. This is achieved without any additional mechanical complexity. This actuator relies on changes to the elastic properties of the elastomer material in response to a secondary stimulus. The elastomer can be switched from a rigid glass-like state to a soft elastic state as required. We present a dielectric elastomer actuator that utilizes shape-memory polymer properties to achieve such state switching. In this case control of the elastic properties is achieved through temperature control. When the material is below its glass transition temperature (Tg) it is in its rigid state and dielectric actuation has no effect. When the temperature is elevated above Tg the material becomes soft and elastic, and dielectric actuation can be exploited. We present preliminary results showing this zero-energy fixity property. Applications are widespread in the fields of robotics and engineering and include morphing wings that only need energy to change shape and control valves that lock rigidly into position.

7642-74, Session 11a

Jamming as an enabling technology for soft robotics

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This paper presents a new architecture in soft robotics that utilizes jamming of a granular medium. We describe a new concept of actuation that modulates the direction and amount of work done by a single central actuator using jamming “activators” to jam and unjam components around the actuator. These ideas are demonstrated in the Jamming Skin Enabled Locomotion (JSEL) prototype which can morph its shape and achieve locomotion. Next, a new actuator denoted a Jamming Modulated Unimorph (JMU) is presented as an alternative to the JSEL topology to better aid navigating through small holes. The JMU uses a central McKibben actuator and a discrete number of jamming cells to turn the 1 DOF McKibben actuator into a multi DOF bending actuator. Full characterization of the JMU actuator is presented, followed by a concluding argument for jamming as an enabling mechanism for soft robots in general, regardless of actuation technology.

7642-75, Session 11a

Performance of multi-segment dielectric elastomer machines

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Dielectric Elastomer Actuators (DEA) have impressive performance characteristics that equal or surpass biological muscle in several respects. But raw performance is of limited utility without the ability to steer motion and work along desired paths. Bio-engineering and bio-robotics applications in particular often involve mimicking the movements of live beings, and require creating devices capable of many more degrees of freedom than in conventional mechanisms.

A simple linear actuator can be constructed by putting the DEA membrane under tension and partitioning its electrodes into two independently addressed segments. As these segments are actuated in turn, one will grow larger while the other shrinks resulting in displacement from the active towards the passive areas. By applying this principle of electrode segmentation and sequential actuation in two dimensions instead of only one it becomes possible to generate richer movement patterns. In previous work we have used it to generate orbital motions that drive a rotating shaft, thus creating a rotary motor.

In this paper we present a generalization of the rotary motor concept that leads to flat actuators capable of complex motions through phased actuation of unequal segments. Mathematical models are developed that provide insight into the relationships between the number and geometry of the electrode segments and the amplitude and curvature of motion. The design of segment shapes to obtain the desired two-dimensional trajectory of a point is examined, and the limits of motion available in multi-segment DEA are explored. Examples are given of actuator segment optimization for square and elliptical trajectories.

7642-76, Session 11b

Hydrogel-based piezoresistive biochemical microsensors

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This work is motivated by a demand for inexpensive, robust and reliable biochemical sensors with high signal reproducibility and long-term-stable sensitivity, especially for medical applications. Micro-fabricated sensors can provide a continuous monitoring and on-line control of analyte concentrations in ambient aqueous solutions. The piezoresistive biochemical sensor containing a special biocompatible polymer (hydrogel) with a sharp volume phase transition in the neutral physiological pH range near 7.4 can detect a specific analyte, for example, carbon dioxide or glucose. Thereby the hydrogel-based biochemical sensors are useful for the diagnosis and monitoring of diabetes and of pulmonary disease. The basic working principle is as follows. A chemical reaction takes place due to the analyte concentration change resulting in a pH change. The latter is detected by means of pH-sensitive gel swelling leading to the deflection of bending plate in piezoresistive pressure sensor. The measured kinetic curves have been analysed by means of appropriate models and some methods improving the properties of the biochemical sensors have been proposed. The polymer film preparation conditions and measurement conditions, which are necessary for high signal reproducibility and high long-term stable sensor sensitivity, were determined. The improvement of sensor properties such as response time, sensitivity, stability and selectivity is discussed for both in vitro and in vivo usages of the implantable sensors.

7642-77, Session 11b

Flexible strain sensor for air muscles using polypyrrole coated rubber

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Air muscle is an important advancement in the field of artificial muscle. However, external sensors are still being used to indicate its displacement or strain. Some of these external sensors are bulky, expensive and impractical for real life applications. The integration of a strain sensor into air muscles would ease the complexity of the hardware system. This would contribute to the development of a complete self-contained system where the actuator and sensor are integrated.

A flexible strain sensor was developed by coating butyl-rubber with the conducting polymer, polypyrrole (PPy) through chemical deposition. Micropores in the rubber were increased using sulphuric acid before PPy deposition to improve adhesion of PPy. PPyThis deposition makes the rubber conductive and the electrical conductivity is determined by the deposited PPy. This flexible strain sensor responses to the strain experienced by the rubber through the changes in electrical conductivity or resistance. Using a wheatstone bridge to determine the electrical response, it was found that the electrical resistance has a positive trend with the applied strain. In addition, the electrical responses could reach to a strain of up to 30%.

The ability to mount the sensor directly onto the air muscle allows for a complete integration, creating a simple actuator and sensor system. As the PPy was deposited chemically, it has no mechanical component, eliminating wear and movement; hence increase in durability and less maintenance. More importantly, it is inexpensive to manufacture and light weight, making this sensor applicable for other applications to measure displacement or strain.

7642-78, Session 11b

Multifunctional shape memory polymers and their composites: fundamentals and applications

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As a novel kind of smart materials, shape memory polymers (SMPs) have been one of the most attractive subjects under intensive investigation in the recent years. Various applications are also explored owing to the their unique advantages, such as large recoverable deformation, lower manufacturing cost, easier pretreatment procedure and lower recovery temperature. Our major researching efforts are focused on the fundamentals and their applications of SMPs and their composites. In this paper, the synthesis of SMPs is presented firstly, with a detailed description of fabrication and processing method. We also investigate the constitutive model of these thermosetting SMPs. The characterization method and main parameters of shape memory effect are described to determine the shape recovery properties of SMPs. Then, different kinds of reinforcement are embedded into SMPs to form smart composite materials, aiming to improve their properties or strengthen the materials. Furthermore, in order to realize the actuation of SMPs for a special application, the investigation of actuations in multi ways are also performed, namely electroactive SMPs, solution activated SMPs, and light-induced SMPs. Finally, based on the unique properties of such materials, primary applications are also studied, including shape memory polymer foam, biodegradable SMPs, morphing wing and space deployable structures, which provide meaningful guidance for further researching works in this area.

7642-79, Session 11b

Electromechanial characteristics of actuators based on carbide-derived carbon

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An electromechanical transducer was prepared using non-ionic polymer, ionic liquid and carbide-derived carbon (CDC). Recently simple layer-by-layer casting method was discovered for actuator production using bucky gel" mixture as a precursor of actuator electrode layers. In this paper we investigate carbide-derived carbon as new alternative candidate to carbon nanotubes to replace nanotubes in electrode layer of transducer. At the initial stage of the study, the ratio of nanoporous high surface TiC-derived carbon powder, 1-ethyl-3-methylimidazolium tetrafluoroborate (EMIBF4) and polymer (PVdF(HFP)) was varied and each formed electrode was analyzed to find out an optimal composition. The results revealed that the optimal component ratio for electrodes is: 35 wt% PVdF(HFP), 35 wt% EMIBF4 and 30 wt% CDC. The assembled three layer transducers were characterized by measuring blocking force, maximum strain, speed and their power consumption and capacitance. The synthesized actuator showed very good force and capacitive characteristics and it is preferable for slow response applications compared to transducers based on carbon nanotubes.

7642-80, Session 11b

Liquid crystal elastomer composite with optimum actuation amplitude

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We have investigated a composite design of spontaneously actuating liquid-crystal elastomer (LCE) and heating wires embedded into the rubbery matrix. We focus on the bistable configuration of wires at a critical angle to actuation direction, which theoretically provides a second energy minimum for wires deforming within an incompressible matrix. Experiments confirmed the practicality of the theory when wires are embedded in a soft matrix such as an elastomer. Two stacking designs were tested: the double layer composite with parallel wires between the layers yields a shape change of 150%, whereas the triple layer composite with wires wrapped around the middle layer gives a change of 130%, with better durability. It is expected that better actuation stroke could be achieved if main-chain LCE layers were used, for which the intrinsic amplitude of thermal contraction can reach several hundreds percent. We also critically evaluate the response time and power efficiency of heat-stimulated LCE actuators. It is found that heat capacity of LCE determines its performance limits for operations

at a fixed ambient (e.g. room) temperature. The combination of critical angle geometry and resistive heating of embedded wires should yield optimum strain achievable by a remote stimulus. It also opens up the possibility of providing large actuation forces by making multi-layer LCE composites.

7642-81, Session 12a

Nonlinear force control of dielectric electroactive polymer actuators

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Electroactive polymer (EAP) based actuators can provide compact actuation solutions to engineering problems in many fields such as: robotics, medical devices, power generation, actuators and sensors. Their characteristics are advantageous over conventional types of actuators due to their lower weight, faster response, higher power density and quieter operation. When considered as actuators an effective controller is necessary to get greater performance out of EAPs, specifically when controlling the amount of force exerted for an interaction between an object and a human. Applications that use EAPs as haptic interfaces could benefit from various controllers. To date little research has been conducted into the force control of EAPs or their possible applications which utilize force control. This paper presents a real-time nonlinear force controller for a Rolled type Dielectric Electroactive Polymer (RDEAP). To increase the response characteristics of the actuator, a control algorithm and non-linear inverse model were derived using the actuator's nonlinear behavior. Experiments have been conducted to compare the response of P, PI and PID controllers both with and without the feed forward non-linear term. A PID controller with the inverse model as a feed forward term has been found to give the fastest rising time (~40ms) and settling time (~50ms). The force controller presented can enhance the safety and performance of this unique family of actuators, allowing for more advanced and efficient applications.

7642-82, Session 12a

Closed loop control of a rotational joint driven by two antagonistic dielectric elastomer actuators

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Dielectric elastomers are a subclass of electronic EAPs able to produce large deformations (and thus mechanical work) when an external electric field is applied.

While the intrinsic compliance of this kind of polymeric actuators have been always addressed as major benefit respect to traditional electromagnetic motors, unable to fully capture the capabilities and mechanical properties of biological muscles, their polymeric nature poses peculiar challenges in controlling a system which is subject to nonlinearities, hysteresis and viscous creep behavior.

In this paper we explore the controllability properties of a simple rotational joint driven by two dielectric elastomer actuators arranged in an antagonistic configuration. A number of sensors are used to obtain information about the state of controlled system: the angular position of the joint is measured by an angular encoder, tension sensors are used to monitor the tension of the two driving tendons and linear encoders provide accurate measurements of the displacements generated by the two actuators. Moreover, the capacitance of the two dielectric elastomer actuators is estimated and used to obtain additional information about the status of system.

Using this feedback information, a control algorithm has been implemented on a microcontroller unit in order to independently activate the two actuators, allowing a closed loop control of both the angular position of the joint (position control) and its stiffness (impedance control).

A detailed description of the developed control strategy and its performances under different load conditions are discussed in this paper.

7642-83, Session 12a

Active vibration control using DEAP actuators

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Dielectric electro-active polymer (DEAP) is a new type of smart material, which when utilised as actuators, has the potential to be used for effective actuation in different applications. DEAP has a range of properties that place it somewhere between those of piezoceramics and shape memory alloys (SMA's).

Among others, active vibration control is one of the application areas where the tubular type DEAP actuators have shown promising performances.

This work, first, introduce DEAP-based tubular actuators produced by Danfoss PolyPower A/S. Static and dynamic characteristics of the actuators are then investigated. Models, describing the static and dynamic characteristics, are developed and compared with experimental results. Different control strategies, used in active vibration control, are investigated and the implications due to unique characteristics of the DEAP actuators, in control design, are assessed. Active vibration control for both tonal and broadband vibrations are considered, and performance of various control strategy for each vibration type is investigated. Experiments, using the designed controllers and the DEAP-based actuators, for tonal and broadband vibration are then carried out. The performance of the DEAP actuators, in tonal and broadband vibration suppression, is illustrated.

7642-84, Session 12a

Hysteresis compensation for an open-loop controlled tubular actuator

J. Oubaek, Danfoss PolyPower A/S (Denmark); R. W. Jones, Univ. of Southern Denmark (Denmark); R. Sarban, Danfoss PolyPower A/S (Denmark)

The development of a precision control system for the DEAP tubular actuator is a basic requirement for commercialisation of the technology. For time-varying reference changes the performance of feedback control, using a conventional proportional and integral (PI) controller, is far from satisfactory with the underlying hysteresis of the powered actuator and the 90 degrees phase lag from the PI controller combining to create a delayed controlled response.

Open-loop control, where the controller is based on an approximate inverse of the actuator model, offers the potential of much improved controlled tracking performance with time-varying reference signals. This contribution examines open-loop control of a tubular actuator with hysteresis compensation being integrated into the control scheme to improve position tracking precision with periodic reference signals. The hysteresis compensation approach used is based on the phaser concept introduced by Cruz-Hernandez and Hayward. A phaser is an ideal frequency domain operator that shifts a periodic input signal by a constant phase-angle without changing the magnitude of the system and this approach provides simple, yet effective, linear compensation of hysteresis.An initial simulation study introduces the ideas behind phaser-based hysteresis compensation. The approach is them applied to a core-free tubular actuator with the hysteresis related phase lag being determined for a range of periodic input voltages. The designed phaser is then implemented into the real-time open-loop control system and improved tracking of the reference signal demonstrated.

7642-85, Session 12a

Flexible enhanced energy density composites for dielectric elastomer actuators

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Dielectric elastomer actuators deform due to voltage-induced Maxwell-stress, which interacts with the mechanical properties of the material. Such actuators are considered for many potential applications where high actuation strain and moderate energy density comparable to biological muscle are required. However, the high voltage commonly required to drive them is a limitation, especially for biomedical applications. The high driving voltage can be lowered by developing materials with increased permittivity, while leaving the mechanical properties unaffected. Here, an approach to lowering the driving voltage is presented, which relies on a grafted nano-composite, in which conducting nanoparticles are integrated directly into a flexible matrix by chemical grafting. The conducting particles are π-conjugated rod macromolecules, which are grafted chemically to a polymer matrix flexible backbone. Dielectric spectroscopy, tensile mechanical analysis, and electrical breakdown strength tests were performed to fully characterize the electro-mechanical properties. Planar actuators were prepared from the resulting composites and actuation properties were tested in two different modes: constant force and constant strain. With this approach, it was found that the mechanical properties of the composites were mostly unaffected by the amount of nanoparticles, while the permittivity was seen to increase from 2.0 to 15, before percolation made further concentration increases impossible. Hence, it could be demonstrated that the so-called “optimum load” was independent from the permittivity (as expected), while the operating voltage could be lowered, or higher strains could be observed at the same voltage.

7642-86, Session 12a

Generation fuzzy rules and learning algorithms for swimming fish robot using IPMC actuators

J. H. Kim, C. Kim, H. Yang, J. Park, Yonsei Univ. (Korea, Republic of)

Nowadays, Research concerned in the artificial life is devoted to understanding life by attempting to abstract the fundamental dynamical principles underlying biological phenomena, and recreating these dynamics in other physical media including computers.

In addition to providing new ways to study the biological phenomena associated with biological life(B-life), artificial life(A-life) allows us to extend our concepts to the larger domain of “life-as-it-could-be”. Swimming fish robot has complicated behaviors and activities to swim in the water. In addition, it is essential that swimming fish robot compose of complex mechanical elements due to taking many complex behaviors. So, we propose Ionic Polymer-Metal Composites (IPMCs) to control swimming fish robot activities. We will acquire good control Mechanical system by IPMCs on swimming fish robot and artificial intelligence algorithms will be obtained by our suggested environment learning algorithms for swimming fish robot.

7642-88, Session 12b

Design and implementation of dexterous robotic hand for human controlled interfaces: a comparative analysis with EAP systems

N. D. Thayer, S. Priya, Virginia Polytechnic Institute and State Univ. (United States)

An anthropomorphic robotic hand with 23 degrees of freedom (DOF), dexterous enough to type on a standard keyboard, has been developed. The design was inspired by human hand physiology. The hand consists of 19 servo motors that drive tendons which run from the forearm to the hand contribute to the system’s human-like functionality and physical appearance. Antagonistic torsional springs and a 4-bar mechanism were utilized to decrease the complexity of control. A kinematic relationship between joint space and end effector was established using Denavit-Hartenberg representation coupled with LabView and Matlab to produce accurate typing motions. The high dexterity will allow future implementation for complex grasping tasks and object manipulation. This paper focuses on the mechanical design analysis and comparison with biological systems for the prototype hand and forearm. This paper will address the advantages and disadvantages of the prototype with respect to electro-active polymer based actuation in terms of motion, power consumption, precision and control.

7642-89, Session 12b

Feasibility analysis of a dielectric elastomer-based ankle-foot orthotic

A. P. Mulgaonkar, M. O. Culjat, W. S. Grundfest, Q. Pei, Univ. of California, Los Angeles (United States)

Several papers in the published literature have discussed using dielectric elastomer-based actuators to provide active control of the ankle-foot orthotics commonly used to treat the drop-foot gait pathology commonly associated with brain/spinal cord trauma, traumatic brain injury, multiple sclerosis, cerebral palsy, and stroke. While dielectric elastomer actuators show promise in this application due to their light weight and high power density compared to traditional actuation methodologies, a working system has not been demonstrated to date. In this paper we aim to rigorously demonstrate the feasibility of such a system. Real-time kinematic gait analysis was used to determine the necessary base-line torque about the ankle-joint and validate existing models of ambulatory motion. Mechanical and electrical analysis of a simple core-free rolled dielectric elastomer actuator was performed to quantify actuation and charging time constants to determine if these parameters are in line with natural gait. Several different actuator positions and orientations based on ankle-physiology were further explored through modeling with and scale-model testing. All this data has been aggregated into a dynamic model-based simulation of active gait assistance with a dielectric-elastomer powered ankle-foot orthotic.

7642-90, Session 12b

Development of a deformable mirror based on conductive polymer actuator arrays for use in adaptive optics

A. D. Price, H. E. Naguib, F. Ben Amara, Univ. of Toronto (Canada)

Adaptive optical systems incorporate active components that compensate for wavefront aberrations introduced by optical defects. The increase in resolution is limited by the stroke of the adaptive component’s underlying actuating mechanism and the differential stroke of neighbouring actuators. This study first explores the design and fabrication of a novel deformable mirror based on electroactive polymers, and more specifically the conductive polymer polypyrrole. A unique Vistec EBPG 5000+ electron beam lithography tool is employed in combination with conventional potentiostatic electropolymerization techniques to produce layered high-density nano-scale polypyrrole actuator arrays. Evaluation of the conductive polymer based deformable mirror is subsequently conducted using a wavefront sensor and the mirror itself as the wavefront corrector. These results indicate that the device delivers superior performance in terms of combined stroke and time response when compared with conventional alternatives such as piezoelectric mirrors or micromachined mirrors utilizing electrostatic electrodes. As this performance was previously unattainable, the implications of this technology are diverse and range from more powerful astronomical telescopes to improved retinal tissue diagnosis. Finally, this investigation serves to demonstrate the successful implementation of electroactive polymers in a complex engineering system.

Conf. 7642: Electroactive Polymer Actuators and Devices (EAPAD) XII

7642-91, Session 12b

A universal dielectric elastomer generator for improved energy harvesting

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Dielectric elastomers are a promising transducer technology that combines low cost, light weight, high fracture toughness, and high energy density. Recent interest in dielectric elastomer energy generators has spurred the development of several designs capable of harvesting energy from a variety of sources from human to wave energy. We have recently reported on a scalable universal dielectric elastomer energy generator that is capable of generating 40 mJ per cycle with an active volume of only 0.57 cm3 and a maximum efficiency of 55%. We build on these results and use recent advances in dielectric elastomer technology to demonstrate an improved generator design. We explore the energy generating characteristics of the generator and compare its performance to theoretical limits.

7642-92, Session 12b

Array of lenses with individually tunable focal-length based on transparent ion-implanted EAP

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We report the fabrication and characterization of 2x2 arrays of mm-diameter lenses, whose top surface is a transparent PDMS EAP actuator, which, when actuated, allows the focal length to be tuned. Arrays of lenses with individually tunable focal length are of interest for laser trapping, beam steering, and imaging. Conventional EAP devices (carbon electrodes) are not transparent, so the polymer actuator cannot also be the lens. However electrodes fabricated by low-energy ion implantation, in addition to allowing conduction at 175% strain and changing minimally the stiffness of the soft elastomer, are more than 50% transparent in the visible. We have developed a chip-scale process to microfabricate arrays of lenses. The array consists of a water-filled socket, on top of which a Pyrex chip is bonded. The Pyrex chip has four through-holes, 1 to 3 mm in diameter, on which a 30 micron thick PDMS (Sylgard 186) layer is bonded. The PDMS layer is implanted on both sides to pattern the electrodes used for EAP actuation with 50 μm resolution. Applying a voltage to one of the lens-actuators leads to an area expansion and hence to a change in radius of curvature, varying the focal length. The devices work in pairs: the actuated device has a decreased focal length, while the fluidically connected un-actuated device has an increased focal length. We report tuning the focal length from 4 mm to 8 mm at 1.7 kV, and present changes in optical transmission and membrane stiffness following gamma and proton irradiation.

7642-93, Session 12b

Biomimetic small scale variable focal length lens unit using electro-active polymer actuators

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Having a combination of a gel-like soft lens, ligaments, and the Ciliary muscles, the human eyes are effectively working for various focal lengths without a complicated group of lens. The simple and compact but effective optical system should deserve numerous attentions from various technical field especially portable information technology device industry. Noting the limited physical space of those deivces, demanding shock durability, and massive volume productivity, the present paper proposes a biomimetic optical lens unit that is organized with a circular silicone lens and an annular dielectric polymer actuator. Unlike the traditional optical lens mechanism that normally acquires a focus by changing its focal distance with moving lens or focal plane. the proposed optical system changes its lens thickness using a annulary connected polymer actuator in order to get image focuses. The proposed biomimetic lens system ensures high shock durability, compact physical dimensions, fast actuations, simple manufacturing process, and low production cost.

7642-94, Session 12b

Active skin on steering wheel

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Conventional technologies, at this time, can not extend to advanced applications which can exploit haptic feel in the human-machine interaction. While dielectric elastomer can be a feasible technology with many good properties, such as soft, flexible, miniature, light weight and high efficiency. So in our research we propose “Active skin using dielectric elastomer”, which contains tactile stimulator and tactile sensor integrated in a single unit. It can sense the contact force (even the position) and transfer the touch feel to the skin such as fingertips, and thus, can use as a haptic interface. Its configuration includes some layers of tactile stimulator, one layer of tactile sensor, and cover by protection layers on top and bottom surface. With large number of cells, when we touch, the active skin can use to determine the force and position at the same time. Independent control of each cell also can give us various choices for surface display. Each cell is designed as a spherical-cap shape to make best support structure for sensing layer, and orient the displacement direction. The controller of active skin uses microcontroller communicates with PC by CAN communication. Microcontroller will receive command from PC and control tactile stimulator part, it also receive sensing signal from tactile sensor part and send back to computer. For example of application we cover the active skin on steering wheel. So the action of steering wheel and operation of active skin can interact with each other.

7642-95, Session 12b

Multilayered low voltage P(VDF-TrFE) actuators built on flexible printed circuit board for microrobot applications

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A multilayered, low weight resonating locomotion module is presented and tested as conveyer. The characterized module has four cantilevers, of which three are used as legs. A lithographically patterned flexible printed circuit board is used as a substrate on which a structure of 14 layers of spin coated poly(vinylidenefluoride-trifluoroethylene) with alternating evaporated aluminium electrodes are deposited. The multilayered electrodes are connected with conductive adhesive after extensive P(VDF-TrFE) has been removed in an plasma etch. By bending the three legs 60° out of the plane using a folding equipment the two dimensional structure is transformed into a three dimensional structure. Three locomotion modules are characterized by connecting them with copper wires. Using the three modules in three different setups the modules are tested with the legs downwards or upside down against a glass plate. By changing the drive voltage and frequency the minimum voltage required for motion is investigated. Successful speed measurements were done already at 1.5 V and the module was capable of forward, backward, right and left movements. With wires attached to it, using a 40 V square wave signal at 18020 Hz, it could move 150 mg, which is more than 37 times it own weight.

Conf. 7643: Active and Passive Smart Structures and Integrated Systems IV

Monday-Thursday 8-11 March 2010

Part of Proceedings of SPIE Vol. 7643 Active and Passive Smart Structures and Integrated Systems 2010

7643-01, Session 1a

Study of a tuned vibration absorber using piezoelectric patches with active shunt circuits

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Tuned vibration absorbers (TVAs) have been extensively used to control vibrations for almost 100 years. The concept of a TVA is very simple. A small mass is attached to a parent structure through a spring. The TVA is tuned to absorb energy and reduce the vibration amplitude at the parent structure's resonant frequency. A TVA can be used to damp a single unwanted resonance or to provide broadband vibration control.

Smart structures represent an opportunity to re-examine TVAs. In this study, a TVA is constructed from a piezoelectric patch and a shunt circuit. A negative capacitance shunt can be tuned to dramatically alter a piezoelectric's stiffness and shift its resonant frequency. The patch is harmonically excited at a frequency near a resonant frequency and the shunt is tuned to match the patch's impedance in a chosen mode, shifting its natural frequency to match the forcing frequency while applying optimal damping. The other modes are observed to determine if impedance-matching a particular mode at a chosen frequency results in broadband damping. The piezoelectric structure is also coupled with a cantilevered aluminum beam. The coupled system is similar to a TVA. In our investigations, the beam is excited at a resonant frequency and the shunt circuit tuned to shift one of the patch's resonances to match the beam's. We observe the extent to which energy from the resonating beam is absorbed by the patch and optimally damped, resulting in damping for the coupled system.

7643-02, Session 1a

Optimizing switching algorithm of synchronized switch damping for multimodal excitation

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Shunted piezoceramics can be used to dissipate vibration energy of a host structure and therefore reduce vibration amplitudes. The piezoceramic converts a portion of the mechanical energy into electric energy which is then dissipated in an electric Network. One semi-active control technique is the synchronized switch damping on inductance (SSDI), which has a good damping performance and can adapt to a wide range of excitation frequencies.

In the standard SSDI a switch is closed during maximum deformation for one half of the electrical period time. This results in an inversion of the electrical charge. For the rest of the half-period the switch is opened and the charge remains constant. This results in a nearly rectangular voltage signal, which is in antiphase with the deformation velocity. In case of multimodal excitation, more sophisticated switching laws are developed with aim to extract vibration energy from higher modes (i.e. 'SSDImax', Richard 2009).

This paper describes a novel multimodal switching law for vibration damping. An observer is designed to obtain an estimation of the first two vibration modes, which are used to determine the switching times. In simulations the increase in energy dissipation is evaluated and compared to the standard SSDI and SSDImax techniques. With the new switching algorithm an improvement in energy dissipation is observed.

The theoretical results are validated by measurements carried out on a clamped-free beam. The location of the piezoceramics is chosen to optimize the electro-mechanical coupling with the first vibration mode of the beam. The modal observer is realized in a realtime environment. Measurements show a good agreement with the theoretical results.

7643-03, Session 1a

Seismic performance of a novel 3D isolation bearing

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Remarkable vertical seismic ground motions and its effect on many modern engineering structures were observed in recent severe earthquake events, but traditional and widely used base isolation system only can effectively mitigate horizontal seismic responses. A promising three-dimensional isolation bearing (3DIB), consisting of laminated rubber bearing with lead core (LRB), combined coned disc spring and steel damper of rhombic steel plate for vertical added damping and stiffness (ADAS), was proposed to mitigate horizontal and vertical structural seismic responses simultaneously and separately. Validation of energy dissipation capacity was performed by numerical simulation. The working mechanism and mechanical characteristics of the novel 3DIB was deduced according to each component. Three-group seismic ground motion records were selected to validate the effectiveness of the proposed 3DIB on a continuous slab bridge, including near-fault seismic records with and without pulse-type character, and often-used seismic records in many time-history dynamic analyses. Transient analysis was carried out for the continuous bridge subjected to these three-group seismic ground motions to validate the effectiveness of the proposed 3DIB. Numerical simulation results of the rhombic steel plate revealed that this steel damper can be dissipated hysteretic energy even in small displacement. The proposed 3DIB is essentially effective to mitigate vertical and horizontal structural seismic response simultaneously and separately. Near-fault pulse-type seismic motions maybe impose enormous horizontal displacement on LRB, which will result in failure of the LRB. Parametric analyses showed that the proper vertical damping ratio is around 20%. The proposed 3DIB is promising to be applied to industrial facilities and even some civil engineering structures to actualize three-dimensional isolation.

This abstract is intended to submit to:

Track 3: Passive and Active Vibration Isolation Systems

7643-04, Session 1a

Twist control of airfoils using a 'reactive' method

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Active twist control of airfoil by means of embedded actuators has been widely studied during the last decade (N.A.S.A., University of Maryland, D.L.R., ...) Here, we propose a method which is to our knowledge new and which make it possible to control the twist by modifications of the internal structure of the profile inducing displacement of the shear center and therefore modifications of the twist moment and torsion angle. This method is only operating if the profile is submitted to an external force. This is why this method is called "reactive". In order to check experimentally the potential of the proposed system, a first demonstrator has been designed for which the structural modifications are done by hand. It is a generic cantilever beam airfoil with span 500 mm, chord 100 mm and thickness 10 mm. The results obtained have shown that for a flexure-torsion load simulating an aerodynamic force, the twist angle at the free end is: 0.09° when the system control is not active and can vary between the ranges 0.35° and -0.17° when the system is active. These first results show the potential of the method proposed. It is possible to induce variations of the twist angle of the order of the static twist angle. In order to improve these results and the method, a second structural demonstrator has been designed making it possible to perform quasi open loop control. The new results will be presented.

Conf. 7643: Active and Passive Smart Structures and Integrated Systems IV

7643-05, Session 1b

Optimum design of bridges with superelastic-friction base isolators against near-field earthquakes

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The seismic response of a multi-span continuous bridge isolated with novel superelastic-friction base isolator (S-FBI) is investigated under near-field earthquakes. The isolation system consists of a flat steel-PTFE sliding bearing and a superelastic NiTi shape memory alloy (SMA) device. Sliding bearings limit the maximum seismic forces transmitted to the superstructure to a certain value that is a function of friction coefficient of sliding interface. Superelastic SMA device provides restoring capability to the isolation system together with additional damping characteristics. The key design parameters of an S-FBI system are friction coefficient of the sliding bearings, initial stiffness and post-yield stiffness of SMA device and yielding displacement of SMA device. The goal of this study is to obtain optimal values for each design parameter by performing sensitivity analyses of the isolated bridge.

First, a three-span continuous bridge is modeled as a two-degrees-of-freedom with S-FBI system. A neuro-fuzzy model is used to capture rate-dependent nonlinear behavior of SMA device. A time-dependent method which employs wavelets to adjust accelerograms to match a target response spectrum with minimum changes on the other characteristics of ground motions is used to generate ground motions used in simulations. Then, a set of nonlinear time history analyses of the isolated bridge is performed. The variation of the peak response quantities of the isolated bridge is shown as a function of design parameters. The results show that the optimum design of the isolated bridge with S-FBI system can be achieved by a judicious specification of design parameters.

TRACK 5

7643-06, Session 1b

Laguerre model based adaptive control of antagonistic shape memory alloy (SMA) actuator

S. Kannan, Univ. Metz (France) and Arts et Metiers ParisTech-Metz (France); C. Giraud-Audine, Univ. Metz (France) and Arts et Metiers ParisTech -Metz (France); E. Patoor, Univ. Metz (France) and Arts et Metiers ParisTech-Metz (France)

In this article Model Predictive Adaptive Control based on a Laguerre parametrization is successfully tested on an Antagonistic Shape Memory Alloy (SMA) actuator.

A usual way to handle the hysteresis is to use a phenomenological or a constitutive model. However, the identification of parameters of the material is a task difficult to realize online due to the nonlinearities of such model.

To adress this problem, an alternative method based on a modified Series-Parallel Model Reference Adaptive Control is used here. It relies on a black box model using a linear parametrization of a Laguerre filters, and the only measurement is the displacement of the actuator. A Recursive Least Square (RLS) algorithm is used to identify the weights of the filter that minimize the error between output of the closed loop control system and the linear Laguerre filter (parallel adjustable system). Using the certainty equivalence principle, a predictive controller gain is tuned online (series adjustable system).

The experimental setup used is a linear antagonistic SMA actuator consisting of two prestressed NiTiNol wires moving a payload. Power is supplied using two voltage amplifiers. The algorithms for online identification and control were implemented using a dSPACE-1104 interface board.

With appropriate tuning parameters the adaptive controller can track different kinds of reference signals. Thermal disturbances added to the either one of the SMA wires are correctly rejected.

The control strategy proposed proved to be able to handle the nonlinearity of the actuator and of the power supply and to reject external disturbances.

7643-07, Session 1b

Shape memory alloy post buckled precompressed (SAPBP) actuator concepts and theory

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This paper explains a new arrangement of shape memory alloy (SMA) actuators. SMA actuators are typically used either antagonistically and/or arranged to move structural components with linearly varying resistance levels, like springs. This generally means that large percentages of strain energy are spent doing work on passive structure (rather than performing the task at hand, like moving a flight control surface or resisting airloads etc.). Post-Buckled Precompressed (PBP) actuators on the other hand are arranged so that the active elements do not waste energy fighting passive structural stiffnesses. Most (if not all) of the PBP actuators of the past have used piezoceramic elements and are highly prone to tensile failure on convex faces. Because SMA actuators are far more tolerant of tensile stresses than piezoceramics, a switch of actuator type is a natural progression of technology.
The paper opens with a short survey on the history of PBP beams and plates. The paper then delves into actuation theory and gives a detailed explanation of the experimental set up. A 6” x 10” test article composed of a glass fiber/ steel composite sheet with SMA wires on top and bottom was used to prove the concept. Substantial deflection and moment generation capabilities were recorded over similarly sized piezoelectrically actuated PBP plates. The paper shows tip rotations on the order of 45° which is nearly triple the levels achieved by piezoelectric PBP actuators. The paper concludes with a discussion of both PBP-controlled and snap-thru dynamics as well as an assessment of future applications.

7643-08, Session 1b

Compressive and tensile deformation behaviors of a Ti-Mo based shape memory alloy

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Ni- free shape memory alloys are promising functional materials for medical applications. A newly developed Ti-Mo based shape memory alloy shows superelaticity after thermomechanical treatment. However,the microstural evolution and precipitation during thermomechanical processes are still not well understood. In the present paper, compressive deformation behavior at a series of temperatures of 298K - 973K and tensile deformation behavior of the alloy after aging at 523K - 973K have been investigated systematically. It is found that the compressive yield stress and ultimate compressive strength change with the deformation temperature in thress stages. The ultimate tensile strength and yield stress of aged samples also change with the aging temperature following a non-linear relationship. Microstructures of aged samples as well as effects of lattice softening and aging-induced precipitates on the deformation behavior have been investigated and discussed.

7643-125, Session 1b

Modeling and optimization of shape memory-superelastic antagonistic beam assembly

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NiTi shape memory alloys (SMA) are the most commonly studied and

implemented SMAs. They gained researchers' attention due to their special properties of shape memory (SM) and superelasticity (SE). In addition, the material is biocompatible (with mechanical properties more comparable to bone than Ti-based compounds or Stainless steel) and has a good resistance to wear and corrosion. The shape memory effect is the recovery of large strains (up to 8%) created in the material while in low temperature by raising the temperature to above a specific level. That specific temperature (called Austenite finish Af) can be manipulated via changing the composition of the material or thermo-mechanical treatment to get a value around body temperature. Superelasticity (SE), shape memory effects (SM), high damping capacity, corrosion resistance and biocompatibility, are properties of NiTi that makes the alloy ideal for biomedical devices

NiTi is used in orthopedic implants as compression staples/clamps for the treatment of bone fracture and anterior fusion of the spine. It is also employed in intramedullary nails that are used to apply controlled force to the bone. Application of NiTi infixation bone plates or rod for the treatment of scoliosis as well as all the aforementioned cases are nowadays common.

The development phase for such applications requires primary modeling and simulation considering NiTi's complicated thermomechanical behavior. There are many models that can capture the performance of shape memory alloys; among them the Tanaka model (later extended by Brinson) was utilized in this study to simulate the behavior of SMA; namely the shape memory effect and superelasticity. In this work, the 1D model developed by Brinson was modified to capture the shape memory effect, superelasticity and hysteresis behavior, as well as partial transformation in both positive and negative directions. This model was combined with the Euler beam equation which, by approximation, considers 1D compression and tension stress-strain relationships in different layers of a 3D beam assembly cross-section.

The algorithm utilizes an iterative method to decide whether the state of the material at every node is in linear elastic mode, i.e. pre or post transformation, or in transformation mode to use cosine-form transformation equations. The algorithm finally solves for the deflection of an SMA beam.

a Shape memory-superelastic NiTi antagonistic beam assembly can be used for enhancing the performance of pedicle screws in osteoporotic bones. A pedicle screw is a particular type of bone screw designed for implantation into a vertebral pedicle. The pedicle screw, which is sometimes used as an adjunct to spinal fusion surgery, provides a means of gripping a spinal segment. The major drawback of spinal surgical treatment with pedicle screws is the lack of strength in degraded osteoporotic bone. The antagonistic assembly consists of a superelastic NiTi (with lower Af temperature) tubular beam and a shape memory NiTi (with higher Af temperature) circular wire that serves as a strength enhancement attachment for pedicle screws.

Proper functionality of this application necessitates an optimization routine to be performed so that the optimum configuration in terms of several variables forming the assembly such as geometry and dimensions can be defined. For the purpose of this study, an objective design is pursued aiming at optimizing the dimensions and initial configuration of the SMA wire-tubing assembly.

7643-09, Session 2a

Long term transducer performance for human motion energy harvesting

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The use of a metallised PVDF film as a transducer for human motion energy harvesting has been investigated. A transducer can be placed between a load and the wearer of the load, to be activated by differential movement between the two, as the wearer walks or performs other duties. From preliminary testing of the film in tension, the electrical energy outputs of the PVDF due to a range of sine waveform mechanical load cases and frequencies, as well as electrical parameters, was determined. This work was performed with the goal of maximising output efficiency. Experimentation was conducted on especially constructed laboratory hardware.

Further investigation has determined the input waveform of a person walking at a range of speeds, whilst wearing a load carrying garment intended for the inclusion of a piezoelectric transducer. This garment was loaded with mass equivalent to that expected in normal usage. The garment was modified by the inclusion of a load cell within one of the supporting straps, which was sampled, and the resulting load waveform stored and plotted. The waveform was then used as an input for further testing of a PVDF film sample, with the goal of determining the long term performance of the material. A film was tested on a large electromagnetic actuator, especially designed and built for the purpose of testing flexible transducer materials. In particular, the performance of a film sample has been studied, indicating that degradation of electrical energy output occurs with an increasing number of mechanical (stress) cycles.

7643-11, Session 2a

Novel two-stage piezoelectric-based electrical energy generators for low and variable speed rotary machinery

R. T. Murray, J. S. Rastegar, Omnitek Partners, LLC (United States)

A novel class of two-stage piezoelectric-based electrical energy generators is presented for rotary machinery in which the input speed is low and varies significantly, even reversing. Applications include wind mills, turbo-machinery for harvesting tidal flows, etc. Current technology using magnet-and-coil rotary generators require gearing or similar mechanisms to increase the input speed and make the generation cycle efficient. Variable speed-control mechanisms are also usually needed to achieve high mechanical to electrical energy conversion efficiency.

Presented here are generators that do not require gearing or speed control mechanisms, significantly reducing complexity and cost, especially pertaining to maintenance and service. Additionally, these new generators can expand the application of energy harvesting to much slower input speeds than current technology allows.

The primary novelty of this technology is the two-stage harvesting system. The harvesting environment (e.g. wind) provides input to the primary system, which is then used to successively excite a secondary system of vibratory elements into resonance - like strumming a guitar. The key advantage is that by having two decoupled systems, the low-and-varying-speed input can be converted into constant and much higher frequency vibrations. Energy is then harvested from the secondary system's vibrating elements with high efficiency using piezoelectric elements or magnet-and-coil generators. These new generators are uncomplicated, and can efficiently operate at widely varying and even reversing input speeds.

Conceptual designs are presented for a number of generators and subsystems (e.g. for passing mechanical energy from the primary to the secondary system). Additionally, analysis of a complete two-stage energy harvesting system is discussed with predictions of performance and efficiency.

This paper is being submitted for SSN03, Track 1: Energy Harvesting Technologies

7643-12, Session 2a

Energy-harvesting power sources for very-high-G gun-fired munitions

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Several novel classes of piezoelectric-based energy-harvesting power sources are presented for very high-G gun-fired munitions (40,000 - 240,000 Gs). The power sources are designed to harvest energy from the firing acceleration and in certain applications also from in-flight vibrations. The harvested energy is converted to electrical energy for powering onboard electronics, and can provide enough energy to

eliminate the need for batteries in applications such as fuzing.

During the munitions firing, a spring-mass system undergoes deformation, thereby storing mechanical potential energy in the elastic element. After release, the spring-mass system is free to vibrate and energy is harvested using piezoelectric materials. Two distinct classes of systems are presented: First are systems where the spring-mass elements are loaded and released directly by the firing acceleration. Second are those which use intermediate mechanisms reacting to the firing acceleration to load and release the spring-mass system.

Description and evaluation of various methods for loading and releasing the spring-mass system in the high-impact environment, as well as packaging for very-high-G survivability are discussed at length. Also included are methods for using the devices as hybrid generator-sensors, how the devices intrinsically provide augmented safety, and methods to increase the efficiency of such power sources for very high-G applications.

Examples of a number of prototypes for complete high-G energy harvesting systems are presented. These power sources have been designed using extensive modeling, finite element analysis, and model validation testing. The results of laboratory, air-gun and firing tests are also presented.

This paper is being submitted for SSN03, Track 1: Energy Harvesting Technologies

7643-13, Session 2a

Strength analysis of piezoceramic materials for structural considerations in energy harvesting for UAVs

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The concept of energy harvesting in unmanned aerial vehicles (UAVs) has received much attention in recent years. Piezoceramic patches attached to the wings of an aircraft can be used to convert naturally occurring wing vibrations into usable electrical energy. In an effort to improve the efficiency of vibration energy harvesting systems, a multifunctional approach to harvesting has recently been proposed by the authors where a single device, known as a self-charging structure, is capable of harvesting energy, storing that energy, and carrying structural load. Self-charging structures consist of piezoceramic layers for energy generation, thin-film battery layers for energy storage, and a central substrate layer. In UAV applications, a critical element of the self-charging structure concept is the ability of the device, particularly the piezoceramic elements, to support aerodynamic loads. Bending strengths of various piezoceramic materials, however, are not well documented in the literature. The second part of this work presents an experimental investigation of the bending strengths of several monolithic piezoceramic materials including PZT-5A and PZT-5H, commercially packaged devices using PZT-5A such as QuickPack and Macro-Fiber Composite (MFC) piezoelectrics, as well as PMN-PT and PMN-PZT single crystal piezoelectrics. A standard three-point bending test is used to quantify the bending strength of each type of material tested. Results of the testing are reported and can be used as a design tool in the development of vibration energy harvesting systems in which the active device is subject to bending loads.

7643-14, Session 2b

A one-dimensional rate-dependent constitutive model for superelastic shape memory alloys

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Shape memory alloys (SMAs) are a relatively new class of functional materials, exhibiting unique thermo-mechanical behaviors, such as shape memory effect and superelasticity, which enable their great potentials in seismic engineering as energy dissipation devices. This paper presents a study of the mechanical behaviors of superelastic SMAs, specially emphasizing on the influence of strain rate under various strain amplitudes. Cyclic tensile tests on superelastic NiTi SMA wires with different diameters under quasi-static and dynamic loadings were carried out to assess their dynamic behaviors. An internal temperature variable which indicates the influence of loading frequency under various strain amplitudes and different temperatures was introduced to the Liang's constitutive equation of SMA. Numerical simulation results based on the proposed constitutive equations and experimental results are in good agreement. The findings in this paper will assist the future design of superelatic SMA-based energy dissipation devices for seismic protection of structures.

7643-15, Session 2b

Shape memory effect and mechanical properties of short fiber reinforced SMP composite

K. Yu, Y. Liu, J. Leng, Harbin Institute of Technology (China)

By adding random distributed short fiber into a shape memory polymer (SMP) matrix, both the mechanical properties and the shape memory behavior are improved significantly, overcoming the traditional defects of SMP composite reinforced by long fiber and particles. In this paper, the short fibers reinforced SMP were developed for the improvement of the mechanical and thermal properties of styrene-based SMP bulk. The specimens with different chopped fiber weight fractions were prepared, and then their mechanical behavior and shape memory effect were investigated. As a result, the resistance against mechanical and thermal mechanical loads in the developed materials increased due to the role of reinforcement fiber. For composite filled with short carbon fiber, not only the actuation of SMP composite can be driven by low voltage, but also its tensile, bending strength, glass transition temperature storage modulus and thermal conductivity increased by a factor of filler content of carbon fiber increased. The results show meaningful guidance for further design and the performance evaluation of such composite materials.

7643-16, Session 2b

Experimental investigation of active rib stitch knitted architecture for flow control applications

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For many years research has been conducted to investigate the potential for actively controlling flow patterns around aircraft wings mid-flight to optimize aerodynamic performance. By delaying or preventing separation of the boundary layer around the wing, improvements in air flow can be achieved which can enhance high-lift capability, reduce drag, and increase maneuvering performance, allowing for increased fuel economy and operation over diverse flight conditions resulting in the ability to complete longer, more difficult missions. Several methods of active flow control during transonic flight have been investigated with great promise including synthetic jets and micro flaps. Surface texturing, however, is an alternative method that has the potential to provide a varied surface profile while maintaining a continuous, smooth aerodynamic structure. The creation of contour bumps has been computationally shown to reduce drag in transonic flight by 24% under certain flight conditions but actively varying the bump height mid-flight and creating longer gradual bumps have posed technical difficulties. Active knits, which are a novel class of cellular structural smart material actuator architectures created by continuous, interlocked loops of stranded active material, are one unique approach to provide this active surface texturing. All active knit stitch patterns are created by a specific array of two basic loop structures - knit loops

and purl loops. One stitch pattern that displays potential to realize flow control applications, among other applications requiring actuation normal to a surface is the rib stitch. This stitch can be used to create the necessary spanwise discrete periodic arrays for flow control across the wing provided it can withstand aerodynamic forces while supplying adequate actuation displacement for flow control. This paper presents a preliminary experimental investigation into the potential of using shape memory alloy (SMA) wire in a rib stitch knit textile for actuation normal to a surface by examining the force-displacement capabilities of the textile. A SMA rib stitch prototype was created and tested to determine the performance and the pre-loaded single stroke deployed actuation capability. Both experimental tests demonstrated promising results, providing practical displacements under large surface pressures comparable to normal-cruise aerodynamic wing loads. The rib stitch active knit architecture may also be able to actuate against higher surface pressures such as those required for flow control as well as the increased wing loading incurred during takeoff, landing, and other flight maneuvers through optimization of material (SMA or another smart material), geometric (SMA wire diameter, course height, wale width, number of courses, and number of wales) and architectural (number of wales per rib) design parameters. Although this preliminary experimental investigation looks at just one possible configuration of design parameters, it demonstrates the ability to create novel, three-dimensional, distributed actuation capable of providing surface texturing under loads similar to aerodynamic forces at typical normal-cruise conditions.

7643-17, Session 2b

Ferromagnetic shape memory flapper

Y. Ganor, Univ. of Minnesota (United States); O. Kanner, D. Shilo, Technion-Israel Institute of Technology (Israel); R. D. James, Univ. of Minnesota (United States)

Flapping mechanisms that generate propulsion for swimming and flying are abundant in nature. One way of obtaining motion is by a transverse movement of surfaces in media which forms lateral thrust, thus propelling the body. Of a great interest are systems that can produce propulsion at scales of millimeter down to a micron, or perhaps smaller. Possible candidates for those tasks are active materials. These materials are commonly applied as actuation devices in Micro Electro Mechanical Systems (MEMS).

Among active materials, shape memory alloys offer the largest work output per cycle accompanied by huge strains. Temperature change induces a structural transformation from austenitic to martensitic phase, thus producing large strains. These materials are attractive for MEMS applications, but for the problem of small-scale autonomous motion, the difficulty of supplying temperature pulses to a moving vehicle seems hard to overcome. Moreover, the ability to generate high gradients of temperature for this motion is limited by the heat conduction of the alloy and its surroundings.

In recent years, a sub class of shape memory alloys known as ferromagnetic shape-memory (FSM) alloys has received much attention because they can provide large strains and have fast responses to external magnetic fields. Unlike temperature controlled shape memory actuation, the ferromagnetic shape memory actuation can also be induced by fast rearrangement of twin variants of the martensite. By applying a magnetic field to the martensitic state, they can be made to undergo large deformations, comparable to that produced by the best shape memory materials.

A new method for propulsion using a Ni2MnGa ferromagnetic shape memory flapper is introduced. We examine the magnetic field induced strain of pure shear by means of a state of the art generator that provides alternating magnetic fields of 7000Oe at frequencies of up to 100Hz. Preliminary measurements show shear deformation of about 5% and thrust forces in the mN range, which open new frontiers in propulsion mechanisms.

7643-18, Session 2b

Development, assembly, and validation of an SMA-actuated two-joint nozzle and six-channel power supply for use in a smart inhaler system

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The smart inhaler design concept recently developed at NC State University has the potential to target the delivery of inhaled aerosol medication to specified locations within the lung system. This targeted delivery could help patients with pulmonary ailments by reducing the exposure of healthy lung tissue to potentially harmful medications. However, controlled delivery can only be accomplished if medication is injected at a precise location in an inhaled stream of properly conditioned laminar flow. In particular, the medication must be injected into the inhaled flow using a small nozzle that can be positioned without disturbing the flow. This paper outlines the procedure used to assemble and control a key component of the smart inhaler: a shape memory alloy (SMA) based dual-joint flexible nozzle that exploits the sensing and actuating capabilities of thermally activated SMA wires. A novel 6-channel power-supply is used to control input power and measure the resistance across the SMA. Since a practical fabrication process may result in SMA wires with different contact resistances, the power supply employs an initialization procedure to self-calibrate and provide normalized power distribution 6 SMA wires simultaneously. Furthermore, a robust control scheme is used to ensure that a constant current is provided to the wires. In validation tests, a LabVIEW-based video positioning system was used to measure the deflection of the nozzle tip and joint rotation. Results show that the carefully controlled assembly of a stream-lined nozzle can produce a practical smart structure, and joint rotation is predictable and repeatable when power input is also controlled. Future work will assess the use of the SMA-resistance measurement as position feedback and PID position control power as a measurement of the convective cooling that results from the moving airflow.

7643-19, Session 3a

Impedance matching for improving piezoelectric energy harvesting systems

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In a piezoelectric energy harvesting system, the dynamic behavior of the mechanical structure as well as the energy flow within the system vary with different harvesting interface circuits connected. Meanwhile, the impedance matching is regarded as theoretical base for harvesting efficiency en-hancement, and hopefully could provide guidance for harvesting interface optimization. Most pre-vious literatures on impedance matching for piezoelectric energy harvesting started their analyses by assuming that harvesting interfaces, which are nonlinear in nature, can be equalized to linear loads, and the load impedance can be arbitrarily set, so that the output impedance of the piezoelectric structure can surely be matched. Yet, after investigating the equivalent impedances of the current existing harvesting interfaces, including standard energy harvesting (SEH), parallel synchronized switching harvesting on inductor (p-SSHI), and series synchronized switching harvesting on inductor (s-SSHI), we found that, their ranges are in fact limited. Therefore, to optimize the harvesting efficiency, constrained matching instead of free matching should be adopted. In addition, we also point out that previous literatures have been confusing for the purpose of matching for energy harvesting. With the understanding on energy flow within piezoelectric devices, we know that only a portion of the extracted energy is able to be harvested, while the other is dissipated throughout the harvesting process. So even the energy extracted from the source is maximized by matching the impedance; there is no guarantee that harvesting efficiency is surely improved. The harvesting efficiency also depends on the ratio between harvested energy and dissipated energy. These two issues discussed in this

article paper are crucial. Without these considerationsing these, the impedance matching method would beis far from ready to be applied to improve the harvesting efficiency.

7643-20, Session 3a

Broadband pipeline vibration energy harvesting

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The quest to harvest energy from ambient vibration has received considerable attention in recent years since sources of mechanical vibration are abundant in many environments. Of particular interest to the oil and gas industry is the use of pipeline vibrations to provide renewable power to various remote electronic sensors that are mounted on a pipeline for the purpose of structural health monitoring. While a wealth of research has been focused on scavenging vibration that is predominantly harmonic, less emphasis was granted to applications where the vibration is broadband by nature, as in the case at hand.

Pipelines conveying gas under pressure exhibit turbulence-induced vibrations. The current work is concerned with extracting useful power from pipelines operating well within their elastic stability region. Under such conditions, the pipeline vibrations exist in small magnitudes and are unlikely to cause structural failure, yet can be exploited to provide useful energy for low-power electronic devices. Accordingly, emphasis in the present work is placed on the development of an energy harvesting technique employing the omnipresent and inevitable flow-induced vibrations in gas pipelines. To this end, the turbulence-induced loads and ensuing structural response are estimated using Large Eddy Simulation (LES) analysis, in conjunction with a finite element model of the pipe under investigation. A piezoelectric resonator, tuned at one of the structural vibration modes, was shown to be an efficient energy harvesting platform. Simplified electrical circuits were employed for signal conditioning to transform the piezoelectric output signals into a more usable form. The phenomenon was simulated experientially on a PVC pipe conveying compressed air that is regulated by an air blower. The findings of the experiments are also confirmed by numerical modeling to illustrate the viability of the proposed design.

7643-21, Session 3a

A novel approach for a piezoelectric broadband vibration energy harvesting generator

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In this study we report H-Shape and Y-Shape piezoelectric transducer structures for harvesting the vibration energy over a broad frequency range. The mechanism for broad band is based upon merging the multiple vibration modes together by exciting complex shapes. The design of H-shape transducer was inspired by tuning fork resonators which are known to posses four distinct modes in close vicinity to each other. Experimental and theoretical results are presented on preliminary transducer design; analyzing their performance in terms of output power and bandwidth (frequency range over which power reduces by half).

The shape of the generators reminds in top view to the letters H and Y respectively. In thickness direction they have a bimorph like structure with a thin metal layer and a top and bottom piezoelectric layer, poled in opposite direction. The electrodes cover the complete top and bottom side. Both generators are mounted vertically in the center to harvest primarily energy from vertical, vibrations.

Due to the complex shape, the systems behavior is investigated theoretically by means of FEM (Ansys) Simulations; the electrical power output is calculated for a mechanically excited system including an equivalent electrical load (complex, linear impedance). To compute the results harmonic analyses are preformed where harmonic excitation and harmonic response are assumed. This type of analysis is used to calculate the frequency response of the generator for different loads and excitation parameters.

To validate the finite element results the generators have been manufactured and characterized experimentally. Analog to the calculations the frequency response has been measured for various loads. Further the vibration shape has been recorded using a scanning laser vibrometer.

The experimental and theoretical results are discussed in detail especially regarding the utilization of the proposed shapes for broadband energy harvesting demands.

7643-22, Session 3a

Piezoelectric energy harvesting from flow excitation: modeling and experiment

A. Erturk, Virginia Polytechnic Institute and State Univ. (United States); W. G. R. Vieira, C. De Marqui, Jr., Univ. de São Paulo (Brazil); D. J. Inman, Virginia Polytechnic Institute and State Univ. (United States)

Among the alternative transduction mechanisms for vibration-to-electric energy conversion, piezoelectric transduction has received the most attention over the last decade. Typically, cantilevers with piezoceramics are used as piezoelectric energy harvesters and the source of excitation is assumed to be harmonic base motion [1,2]. Utilization of flow excitation has been mainly investigated by means of windmill-type conventional devices, which cannot be embedded into several engineering structures, such as aircraft wings. This paper presents lumped-parameter and distributed-parameter piezo-aero-elastic models for energy harvesting from unsteady aerodynamic loads due to flow excitation. Model predictions are compared against the experimental results for the flutter case.

Energy harvesting from flow excitation and aeroelastic vibrations have been investigated by a few authors. Power generation from vortex excitation of a piezoelectric membrane behind a bluff body was investigated by Allen and Smits [3] experimentally. A theoretical work simulating energy harvesting from aeroelastic vibrations of a typical section was presented by Bryant and Garcia [4]. A finite element piezo-aero-elastic model was given by De Marqui et al [5] with simulation results for energy harvesting from a generator wing. A complete work covering both the theory and experiment for energy harvesting from aeroelastic vibrations has not appeared in the literature. This paper aims to provide both lumped-parameter and distributed-parameter piezo-aero-elastic energy harvester models for power generation from flow excitation. Experimental results are presented for model verification.

Figure 1a shows a schematic of the well-known typical section under flow excitation [6]. The governing equations of this system with piezoelectric coupling can be given by where the mechanical degrees of freedom are the pitch ( ) and plunge (h) displacements and the aeroelastic loads (L and M) are obtained from the Theodorsen model [7]. For the maximum electrical energy generation, the flutter case is considered, which agrees with the harmonic motion assumption of the unsteady aerodynamic model considered here.

Figure 1b displays the experimental setup representing a typical wing section in front of a blower. This setup is used for verification of the lumped-parameter piezo-aero-elastic model.

Figure 1. (a) Typical wing section with pitch and plunge degrees of freedom and (b) the experimental setup representing a typical section under flow excitation

Distributed-parameter modeling of a cantilever with piezoceramics under flow excitation will also be given along with the experimental results. An electromechanical bending-torsion formulation is employed based on the thin beam theory by taking the aerodynamic loads from the Theodorsen model [7].

Keywords: Piezoelectricity, aeroelasticity, energy harvesting, vibration,

flow excitation

Track 1: Energy Harvesting and Scavenging

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7643-23, Session 3a

Power-amplifying strategy in vibration-powered energy harvesters

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A new cantilevered piezoelectric energy harvester of which the lumped mass is connected to a harmonically oscillating base through an elastic foundation is proposed for maximizing generated power and enlarging its frequency bandwidth. The base motion is assumed to provide a given acceleration level. Earlier, a similar energy harvester simulating a dynamic vibration absorber was developed but the mechanism of the present energy harvester is new because it incorporates a mass-spring system in addition to a conventional cantilevered piezoelectric energy harvesting beam. Consequently, the proposed energy harvester actually forms a two-degree-of-freedom system. After presenting an overall mechanism of the developed energy harvester, it will be theoretically shown that the output power can be indeed substantially improved if the fundamental resonant frequencies of each of the two systems in the proposed energy harvester are simultaneously tuned as closely as possible to the input excitation frequency and also if the mass ratio of a piezoelectric energy harvesting beam to a lumped mass is adjusted below a certain value. The performance of the proposed energy harvester will be first checked by numerical simulation using ANSYS and then verified through several numerical experiments. It will be also shown that the trade-off between the output power and the output frequency bandwidth can be made by adjusting the mass ratio.

7643-25, Session 3b

Periodic piezoelectric sensor-actuator array for vibration suppression on a beam

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The use of piezoelectric patches for actuation as a vibration control method has been widely investigated. Some of the uses for piezoelectric actuators include velocity feedback, synthetic impedance control, as well as a shunted sensor-actuator. Likewise, periodic structures have been shown to be effective in allowing the dissipation of traveling wave energy. The combination of these control procedures, an active periodic piezoelectric array, allows for enhanced vibration control. Presented here is the investigation of thin beam with 16 piezoelectric patch pairs. These patches will be shunted with varying selected impedances to allow for comparison of control ability. This comparison includes an analysis of spatial RMS velocity, traveling waveform shape, and wave power reduction through the patch array.

7643-26, Session 3b

Active vibration control with optimized modified acceleration feedback equipped with adaptive line enhancer

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The modified acceleration feedback (MAF) controller, an active vibration control method that uses collocated piezoelectric actuator actuators and sensors, is developed using an optimal controller. The control mechanism consists of two main parts: 1) Frequency adaptation mechanism that uses Adaptive Line Enhancer (ALE), and 2) optimal controller. Frequency adaptation only tracks the frequency of vibrations using ALE. The obtained frequency is then fed to MPPF compensators and the optimal controller. This provides a unique feature for MAF, by extending its domain of capabilities from controlling tonal vibrations to broad band disturbances. The optimal controller mechanism consists of a set of optimal gains for wide range of frequencies that is provided based n the characteristics of the system. Based on the tracked frequency, the optimal control system decides to use which set of gains for the MAF controller. The gains are optimal for the frequencies close to the tracked frequency. The numerical results show that the frequency tracking method that is derived has worked quite well. In addition, the frequency tracking is fast enough to be used in real-time controller. The results also indicate that the MAF can provide significant vibration reduction using the optimal controller.

7643-27, Session 3b

Numerical and experimental investigation for centrifugal loading effect on shunted piezoelectric damping

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Newer high-performance turbomachinery blade designs have led to decreased blade damping and higher vibratory stresses. Designing damping treatments for rotating blades in an extreme engine environment is difficult. Several damping methods have been investigated at NASA Glenn Research Center for use in aircraft engines, including viscoelastic damping, impact damping, plasma sprayed damping coatings, and high-damping high-temperature shape memory alloy materials. The current effort seeks to investigate the ability of shunted piezoelectric materials to damp vibrations of rotating turbomachinery blades. While ample research has been performed on the shunted piezoelectric material to control the structural vibration damping, very little study has been done for rotational and temperature effects. Experimental test and analysis are performed for both non-spinning and under centrifugal loading with the plate speciemens. The finite element (FE) simulations are also performed using the ANSYS Multiphysics code which can supports piezoelectric coupled-field elements and electric circuit elements used for the resistor-inductor circuit simulations. Passive and active resonant damping control test results show that shunted piezoelectric damping control techniques obtained in this study have a great potential to be able to reduce plate vibrations under centrifugal loading at room temperature and under vacuum conditions. The FE results also show a good correlation with experimental test results. The validated numerical models and the experimental test results obtained from this study will allow us to extend our current effort for design and optimization of more complex turbomachinery rotor blade systems.

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7643-28, Session 3b

Multimodal vibration control of a flexible beam and plate using multilayered piezoelectric film sensor/actuator

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In the authors' previous reports, it was shown that piezoelectric films were able to be used as sensors and as actuators simultaneously for free or forced vibration control of flexible thin structure without affecting total weights and motion characteristics of the structures. In these methods, piezoelectric film sensor and actuator were shaped using the equivalent shaping functions and were collocated bonded on the surfaces of the beam, the ring and the plate. Direct velocity feedback control was successfully applied to increase damping effects to the first vibrational mode. However, multimodal active vibration control experiments using these high-polymer piezoelectric films were difficult in several reasons. Included in these difficulties were the unstable vibrations due to the electromagnetic interactions between the sensor and the actuator, and the phase lag included in the transfer functions of the controller in high frequency area. In order to overcome these difficulties, it was proposed in this paper to shape piezoelectric sensor and actuator using different shaping functions. At first, fundamental equations were derived and vibration responses of the structure were derived based on the modal coordinate systems. Then, it was shown that by considering phase characteristics of the velocity feedback controller in conjunctions with the polarity of the piezo films in higher order modal frequencies, multimodal control will be implemented both theoretically and experimentally. Finally, numerical and experimental results for flexible beam and plate were shown. (TRACK 3: Passive and Active Vibration Isolation Systems)

7643-30, Session 4a

A magnetically sprung vibration harvester

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The requirement to monitor safety critical systems in remote and harsh environments using Wireless Sensor Nodes (WSN) is becoming more important. Traditionally, WSNs are supplied energy from batteries, however these limit the WSN, due to their need for frequent replacement or recharging. Ideally a WSN would be completely autonomous such that its benefits can be exploited. To achieve this, an alternative source of energy to batteries is required. Energy can be supplied to the WSN by means of 'harvesting' otherwise unused energy from the local environment into a useable form.

This paper will discuss the topology and properties of a magnetically sprung vibration generator that can harness mechanical vibrations. The topology comprises three annular permanent magnets arranged laterally, with opposite magnetisation directions, along a shaft. The two outer magnets are fixed to a frame and the central magnet, which is free to move, is suspended between these, due to the repulsive forces it experiences. The resultant experienced force acts as an equivalent suspension that behaves like a hardening spring. When the frame is excited the central magnet will pass through a co-axial coil inducing a current if a load is connected.

The paper will present a complete model of the system focussing on spring characteristic of the magnetic suspension. The non-linearity of the suspension mechanism yields a non-linear response resulting in a bi-stability and associated 'jump' phenomenon. This non-linearity is validated against measurements. Due to the non-linear suspension two measured load-power curves, corresponding to the upper and lower bounds of the bi-stability result. Those predicted by the model, correspond well with the measured values at the upper bound of the bi-stability. The bi-stability phenomenon can be usefully exploited in developing a vibration harvester with a broad resonant response. This will be useful in an environment where there are either multiple or varying dominant excitation frequencies. An additional property of the system that can be exploited in such or unknown environments is its ability to 'tune' its resonant response. This can be achieved by changing the distance between the outer magnets as the suspension is dependant on this. These attributes will be discussed in detail in the paper.

The paper will also detail the developed non-linear model of the system and will compare results with measurements from the prototype. Derivations of other parameters such as the systems mechanical damping and electromagnetic coupling coefficient will also be described. The paper will also compare the magnetically suspended device's performance against other vibration harvesting devices reported in the literature using figure of merits such as power density and system effectiveness.

TRACK 1: Energy Harvesting and Scavenging

7643-31, Session 4a

Nonlinear vibrations of the piezo-electromagnetic structure for energy harvesting

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A nonlinear energy harvesting structure is proposed to convert ambient vibrations to the electric energy using the piezoelectric and electromagnetic mechanisms. Harvesters potentially eliminate the need to change batteries of standalone electric devices and are crucial for hard to reach sensors, such as those used for structural health monitoring. A typical vibrational energy harvesting device consists of a spring (possibly a cantilever beam) connected to a mass. As the base vibrates the spring deflects and the stress energy created in the spring can be converted to electrical energy. There are two challenges in design of vibrational energy harvesters. The first is the necessity to have a low frequency structure. The frequency of the common ambient vibrations is between 0.1 to 100 Hz. The challenge is to design a structure which can sustain the vibrations while having a low natural frequency. The second challenge is to have a broad band energy harvester. The power outputs of conventional harvesters are orders of magnitude higher if they are excited at their natural frequency but this high power is only available over a few Hz window. The stochastic nature of the ambient vibrations requires the harvester to be less sensitive to the excitation frequency.

Fig. 1: Nonlinear Piezo-electromagnetic harvester

The proposed nonlinear multi physics energy harvester (depicted in Fig. 1) is realized by placing a rare earth magnet at the tip of a bimorph. Another permanent magnet is placed right bellow the beam in its undeformed configuration. The same poles of the two magnets face each other so that there is a repulsive force acting between the two. The placement of magnets will introduce a nonlinear softening term to the lateral force - displacement relation of the cantilever beam.

The paper first formulates the nonlinear governing equation of the beam deflection and the two electromechanical relations between the voltages from the Piezo patch and the magnets and the tip velocity of the beam. The identified three dimensional system is analyzed using the method of multiple scales and the projection method to study the bifurcations of the system. By decreasing the distance between the magnets the nonlinear softening effect intensifies. At first the typical vibration of a weekly nonlinear system is observed which translates to more frequency bandwidth and the useful jump phenomenon. If the nonlinear magnetic force is increased further, the structure goes through a chaotic motion for moderate base excitations and it can go through limit cycle oscillations if the amplitude of base excitation is higher. The chaotic oscillations result in higher electrical energy resulted from a given base excitation. Moreover, the chaotic vibrations are way less sensitive to base excitation frequency and therefore a nonlinear harvester with chaotic behavior has a wide bandwidth of energy production. The analytical study performed, identifies the thresholds of magnet distance and other parameters which result in chaotic vibrations. The predictions facilitate the design of a nonlinear harvester. Finally the experimental setup in Fig.2 is used to examine the accuracy of the analytical predictions and to illustrate the usefulness of

the proposed design in action.

Fig. 2: The experimental setup

7643-32, Session 4a

Self-contained active fluid mount

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Active fluid mounts have not been as widely used as passive fluids mounts in aerospace application due to a need for a source of power and a controller and the need to bring this power and control signal to the mount via wiring harness. In order to resolve these issues, a self-powered self-contained active fluid mount is developed.

The proposed new design consists of a conventional passive fluid mount, and two voice coils. The first voice coil, placed in the lower chamber of the passive fluid mount, acts like an actuator and it changes the volumetric stiffness of the bottom chamber to provide a wide band notch frequency. And the second voice coil acts as an energy harvesting device which is connected to the engine and converts the engine vibrational energy to electrical energy.

The amplitude and phase of the induced current in the energy harvesting device is modified through a passive electrical circuit and applied to the voice coil actuator.

This active mount is modeled using bond graph modeling technique and MATLAB. Dynamic stiffness, required current for the voice coil actuator, and the induced current in the energy harvesting voice coil are plotted. Realistic parameters were implemented into the MATLAB model and it is shown that in a wide frequency range, the induced current in the energy harvesting voice coil is larger than the required current of the voice coil actuator. Therefore, the need for an external source of power is eliminated.

7643-33, Session 4a

The influence of power harvesting circuits on energy harvesting performance

D. Quinn, The Univ. of Akron (United States); S. G. Burrow, D. K. Barton, Univ. of Bristol (United Kingdom)

We consider the performance of a vibration based energy harvesting with realistic topologies for the electrical circuit. Specifically we apply a novel perturbation approach to describe the time-varying power harvested in the system, including a rectifier in the circuitry. This approach considers the full electromechanical coupling between the mechanical and electrical components, including the amplitude and phase of the mechanical response. The resulting analysis is able to describe the behavior of the system as the mechanical response is detuned from resonance by the electrical load. In addition, the charging of the circuit over time is also captured by the analysis. Finally, experimental results are compared against the analytical predictions to verify the analytical approach.

7643-34, Session 4a

Effective energy harvesting devices for railroad applications

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This paper presents the results of the design and development of a new generation of energy harvesters for railroad applications. The onboard and wayside applications of many smart devices that can add to the efficiency of rail operation are often hindered by the lack of availability of electrical power on railcars or at remote track locations. Although ideas such as Timken's Generator Roller Bearing exists, the railroads have been slow in adopting them for various reasons, including the cost premium over traditional tapered roller bearings and the need to include a non-standard part in their material inventory. For wayside applications, although the use of solar panels are starting to gain some attention they are yet to be widely used on railroad tracks due to their high maintenance, dependability on geographical location and daylight, and high cost-to-power efficiency. Some predict that we are still decades away from having solar panels that can be used for general use in a cost effective manner.

This paper will describe the work that we currently have underway for exploring vibration-based electromechanical energy harvesting systems that can be readily installed on railcars and at trackside. Such devices are expected to remedy the short comings of the energy generators that are currently available. Additionally, they will vastly improve on the performance of the piezoelectric-based (PZT-based) energy harvesting systems that have been investigated in the past. Although PZT-based systems work well for many applications that require a minimal amount of energy-such as, operating micro-electronics-they have consistently proven to be too fragile for most rail operations and not able to generate sufficient electricity for running most devices that are of practical interest to the railroads. In contrast, vibration-based systems are mechanical in nature, can be sized according to the amount of energy that they are expected to generate, can tolerate the demands of the railroad operation, and provide more Watts-per-dollar, when compared to both PZT-based systems and the generator roller bearings.

7643-35, Session 4a

Optimal and sub-optimal power management in broadband vibratory energy harvesters with one-directional power flow constraints

J. T. Scruggs, Duke Univ. (United States)

TRACK 1: ENERGY HARVESTING AND SCAVENGING

In many applications of vibratory energy harvesting, the external disturbance are most appropriately modeled as broadband stochastic processes. Optimization of power generation from such disturbances is a feedback control problem, and solvable via a LQG control theory. However, attainment of this performance requires the power conversion system which interfaces the transducers with energy storage to be capable of bi-directional power flow, and there are many applications where this is infeasible. One of the most common approaches to power extraction with one-directional power flow constraints is to control the power conversion system to create a purely resistive input impedance, and then to optimize this effective resistance for maximal absorption. This paper examines the optimization of broadband energy harvesting controllers, subject to the constraint of one-directional power flow. We show that as with the unconstrained control problem, it can be framed as a "Quadratic-Gaussian" stochastic optimal control problem, although its solution is nonlinear and does not have a closed-form. This paper discusses the mathematics for obtaining the optimal power extraction controller for this problem, which involves the stationary solution to an associated Bellman-type partial differential equation. Because the numerical solution to this PDE is computationally prohibitive for harvester dynamics of even moderate complexity, a sub-optimal control design technique is presented, which is comparatively simple to compute and which exhibits analytically-computable lower bounds on generated power Examples will focus on mW-scale piezoelectric bimorph energy harvesting systems, inertially excited by random vibration of the base mount.

7643-36, Session 4b

A dual adaptive tunable vibration absorber using MREs for vehicle powertrain vibration control

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This paper presents a dual Adaptive Tuned Vibration Absorber (ATVA) which uses enhanced magnetorheological elastomers (MREs) for torsional vibration control of a vehicle powertrain system in the steady stage. The MRE used in this application is a soft MRE with a significant MR effect (the increase in elastic modulus is up 100 times in a magnetic field flux intensity B up to 0.5 Tesla). Thus, each single ATVA using the MRE can operate effectively in a much wider working frequency range than a classic dynamic absorber does. In this application, the dual ATVA is proposed rather than a single ATVA because of two main reasons. The first one is that the effectiveness of a single ATVA for the primary powertrain, which is modeled as a four-degree-of-freedom system, depends on not only the ATVA parameters such as inertia, stiffness and damping coefficients but also on the powertrain vibration mode shapes. In other words, if a single ATVA is installed at a fixed position in the powertrain, it may work effectively only with one or few powertrain frequencies. That means this single ATVA will not be able to deal with resonances happening at the other powertrain frequencies although these frequencies are in its working frequency range. The second reason is that a single ATVA cannot deal with two or more resonances at the same time while vehicle's engine fluctuation torque is a multi-frequency excitation because of the internal combustion engine features (that means the powertrain is often subjected to a multi-harmonic fluctuation torque). This paper also proposes a concept design of the dual ATVA. According to the design, the MRE material plays a role as torsional springs, whose stiffness and damping coefficients are controlled by magnetic circuits attached to the dual ATVA. In addition, in this paper the MRE shear modulus is approximated by a cubic polynomial of MRE magnetic field flux intensity B. The proposed approximation is compared to the experiment data of the soft MRE material and they are in agreement. This approximation is convenient for tuning each single ATVA frequency as well as analyzing the vibration of the combined system, which consists of powertrain and the dual ATVA. The numerical simulations of the combined system are used to validate the dual ATVA proposed design. The simulation results showed that resonances happening to powertrain natural frequencies can be deal with. By using the dual ATVA, powertrain resonant frequencies are shifted away excitation frequencies so that powertrain vibration response is significantly suppressed. In addition, the effect of the dual ATVA parameters such as inertia moment, stiffness and damping coefficients to its effectiveness were examined. Furthermore, several location combinations of single ATVAs are examined to find the best combination for the powertrain system in this study. The dual ATVA will be a useful device for powertrain vibration suppression. The effectiveness of the dual ATVA for powertrain vibration during transient stage, when excitation frequencies of fluctuation torque are not constant but vary with the time, over a frequency range will be our next work.

(Track 3: Passive and Active Vibration Isolation Systems)

7643-37, Session 4b

Design and control of multifunctional actuators for assistive knee braces

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(Track 4: Magneto Rheological Systems)

Assistive knee braces are a type of wearable equipment that can enhance people's strength and provide desired locomotion. It is possible to use knee braces to assist elderly or disabled people improving their mobility so as to solve many daily life problems, like going up and down stairs and over obstacles. In addition to support human body, smooth and comfortable locomotion is also desirable for assistive knee braces. The actuation system should not only provide desired torque, but also have the ability of agile and accurate control in various conditions. To assist the wearer in various postures and prevent knee braces from exceeding the restricted motion, actuators should also function as brake/clutch with the feature of safety interlock. Furthermore, power consumption in the actuation system is another consideration in lengthening the working time of batteries after fully charged. Therefore, well designed actuators with appropriate control algorithm would be the key component of assistive knee braces in terms of performance and safety.

In this research, a magnetorheological fluids based compact multifunctional actuator for assistive knee braces is designed. With MR fluids, the actuator possesses multiple functions as motor, clutch, and brake while meeting the requirement of normal walking as well. The objective of this paper is to design and control the multifunctional actuator. Position control, speed control, force and acceleration control are considered. The simplified modeling of the actuator with gearbox as well as controller is presented and the control system is designed. Controllers like PID control and impedance control are adopted in the system. Experimental results show that the motion control of the actuator can be well implemented.

In addition to the system motion control, each function of the actuator is investigated. For motor function, the actuator could work well as the servo system for controlling the position, speed, and force output. In another operation as clutch, the actuator could adjust the torque transferred from the rotor to outside and provide safety to prevent the system from exceeding the restricted motion. Compared with conventional electric motor, the force and acceleration control in brake function is easier to be implemented for the multifunctional actuator. By cooperating among all three functions, the actuator could also fulfill the positioning task as a stepping motor.

To be applied for assistive knee braces, a normal human walking gait is illustrated. According to the gait cycle, at the state of stance flexion and extension, the actuator works as brake; at the state of pre-swing and swing extension, the actuator works as motor and clutch; at the state of swing flexion, the actuator works as clutch. To conduct experiments, angle position and torque references are given for the multifunctional actuator to track the desired motion. The results show that the multifunctional actuator is promising for assistive knee braces.

7643-39, Session 4b

A compressible magnetorheological fluid damper-liquid spring for controllable suspension system

P. Raja, X. Wang, F. Gordaninejad, Univ. of Nevada, Reno (United States)

In this feasibility study a small-scale prototype compressible magneto-rheological fluid damper - liquid spring (CMRFD-LS) for a tracked vehicle suspension system is designed, developed and tested. The goal of this study is to develop a CMRFD-LS device which will have a stiffness of 1.19 x 106N/m under a stroke of 10.16cm (4in) and a considerable controllable dynamic damping force range under an applied magnetic field. The proposed device consists of a cylinder and piston-rod arrangement with an annular MR valve. The internal pressures in the chambers on either side of the piston develop the spring force, while the pressure difference across the MR valve produces the damping force, when the fluid flows through the MR valve. A fluid mechanics-based model is conducted to predict the behavior of the damper device under sinusoidal input. The performance of the device, filled with pure silicone oil and MR fluid, is studied under oscillatory vibrations for various frequencies and applied magnetic fields. The experimental results are in good agreement with the theoretical predictions.

7643-40, Session 4b

Design and testing of a magnetorheological damper to control both vibration and shock loads for a vehicle crew seat

A. Becnel, W. Hu, Univ. of Maryland, College Park (United States); G. J. Hiemenz, Techno-Sciences Inc. (United States); N. M. Wereley, Univ. of Maryland, College Park (United States)

A magnetorheological shock absorber (MRSA) prototype was designed, fabricated and tested to integrate semi-active shock and vibration

mitigation technology into the existing EFV (Expeditionary Fighting Vehicle) forward seating positions. The MRSA was designed so that it could both isolate occupants from whole body vibration (WBV) during normal operations, as well as reduce occupant lumbar loads during extreme events such as rogue waves or ballistic/UNDEX shock events. The MRSA consists of a piston with a flow-mode MR valve having an annular cross-section, a magnetorheological (MR) fluid cylinder, and a nitrogen accumulator. Piston motion forces MR fluid to flow through an MR valve, where it can be activated by a magnetic field. Utilizing Bingham-plastic (BP) constitutive fluid relationships and a steady state fluid flow model, the MR valve was designed using magnetic circuit analysis, and subsequently validated via electromagnetic finite element analysis (FEA). The MRSA prototype was tested at low speeds (vibration mode) and high speeds (shock mode) on a servohydraulic testing machine as well as a rail-guided drop test stand, respectively. A refined hydromechanical model was developed that includes compressibility effects within the damper system and predicts the time response under cyclic or impact loadings. This model was then validated using the measured test data. Key design considerations for the MRSA to accommodate both vibration and shock spectra using a single MR device are presented.

7643-41, Session 4b

Force characteristics of a modular squeeze-mode magneto-rheological element

M. J. Craft, M. Ahmadian, A. Farjoud, W. Burke, C. Nagode, Virginia Polytechnic Institute and State Univ. (United States)

While few publications exist on the behavior of MR fluid in squeeze mode, devices using squeeze mode may potentially take advantage of the very large range of adjustment that squeeze mode offers. Based on results obtained by modeling and testing MR fluid in a squeeze mode rheometer, a novel compression-controlling device has been fabricated and tested, which utilizes the squeeze mode of the MR fluid. The device, consisting of a flexible cylindrical membrane fastened at each end to a steel endplate (pole plate), was tested in a squeeze mode rheometer and compared with simulated results.

While many commercial dampers exist today that utilize MR fluid, these devices all typically operate with the fluid in shear or valve mode. While these modes work well in damping applications, recent modeling and testing with MR fluid in squeeze mode has revealed much higher force ranges are obtainable. Given this, a controllable MR device was designed, fabricated, and tested to take full advantage of the squeeze mode operation.

One significant problem concerning the design of this MR device, known as an MR Pouch, was to find a flexible membrane material that would not degrade or leak after extended periods of contact with oil-based MR fluids. After significant effort, an affordable and practical pouch material was fabricated for a prototype device. The flexible membrane, consisting of a two-part silicone rubber was commercially available and could be made into the required shape for use in the rheometer.

The MR Pouch design uses a novel approach for implementing squeeze mode control. The MR fluid is completely self-contained and does not require an external reservoir to compensate for the volume change between the pole plates. Because the flexible membrane compensates for volume changes, there is no need for dynamic seals and associated surface finish treatments. Additionally, MR Pouches are scalable depending on the application.

Based on modeling refined for the initial squeeze mode rheometer testing, a model of the MR pouch was developed. This model was verified by comparison with data collected on a MTS load frame. The results of the MR pouch were extremely promising for small displacements, where the compression force could be varied from less than 10lbs to greater that 1000lbs. The compression force required was dependent on both the displacement (distance between the pole plates) and the current going to the electromagnet. Additionally, the magnetic field density, B, was also recorded during all of the tests to correlate the change in magnetic field flux density in the fluid due to the position of the pole plates.

7643-42, Session 4b

Structural considerations in designing magnetorheological fluid mounts

T. M. Nguyen, Univ. of Minnesota (United States); C. Ciocanel, Northern Arizona Univ. (United States); M. H. Elahinia, The Univ. of Toledo (United States)

Modern vehicles have been increasingly equipped with advanced technologies such as hybrid and cylinder-on-demand to enhance fuel efficiency. These technologies also come with vibration problems due to the switching between the power sources or the variation of the number of active cylinders. The challenge has been addressed by a large variety of vibration isolator designs ranging from passive to active. Semi-active mounts have caught the attention thanks to their adaptive nature with affordable price. Among the semi-active categories, the magnetorheological fluid (MRF) mounts have been proven to be a highly potential solution to modern vehicle vibration isolation. The reasons are due to the responsive changes in characteristics of the mount when a magnetic field is present without involving with any moving components.

This study looked into several innovative designs of the MRF mounts. The characters of the MRF mounts depends significantly on the compliances of the rubber, the number and arrangement of the fluid chambers and the number of the flow passages connecting each pair of the chambers. These parameters provide the designers with various options to design the mounts to function in changing conditions and a wide range of frequencies. Different values of the aforementioned parameters were selected to form specific designs with certain characteristics. The magnetorheological effect plays the role of proportionally controllable valves installed at the flow conduits. The states of the MRF valves determine the stiffness and damping of the semi-active mounts.

The research is planned to include two phases: analytical modeling and experimental validation. This paper summarized the procedure of the first step, i.e. analytical study. The research was started by constructing mathematical model for each design. The models were simulated in MATLAB/Simulink© to show the design's behavior. The advantages and disadvantages were highlighted with considerations from the vibration isolation perspectives. The categories used for the mount assessment includes the structure, the performance and the cost. This study can be used as a useful reference source for MRF mount designers.

No control algorithm was considered in this research in order to emphasize the importance of the mount construction. The hydraulic and magnetorheological (MR) effects are dominant in the mount, so the elastomer is considered linear.

7643-129, Session 4b

Simulated and experimental flow evaluation for a magnetorheological fluid based micropump

N. Bruno, A. Kipple, C. Ciocanel, Northern Arizona Univ. (United States)

This paper presents simulated and experimental results for a magnetorheological fluid based micropump. The pump is simulated as a micro-electro-mechanical-system (MEMS) and the departure from a classical Newtonian flow is considered. The development of a magnetorheological fluid based micropump is motivated by the elimination of the mechanical moving parts, usually required to sustain the flow, by the bidirectional flow capability achieved by simply switching direction of the electrical current passing through electromagnets, and by the high level of controllability that leads to a wide range of achievable micro-flowrates. In order to optimize the pump output, several geometric configurations, together with different materials selection, were simulated and the advantages and disadvantages of each configuration are discussed. The optimal configuration was replicated experimentally facilitating the comparison of simulated and measured flowrates. To this end, the difference

between the simulated and experimental results is larger than 15%; the reasons for this level of error are discussed in detail and potential improvement solutions are suggested.

7643-43, Session 5

High efficient energy harvesting using piezo macro fiber composites on vibrators with optimized energy transfer

T. P. Daue, J. Kunzmann, Smart Material Corp. (United States); A. J. Schönecker, Fraunhofer Group (Germany)

Harvesting energy from “waste” vibration present in the environment has seen an increasing interest during the past years as part of the general heightened awareness for alternative energy sources. Beside of typical electro mechanical methods, ferro electric devices have proven to be very effective to harvest energy for low power devices as often found in portable electronics, sensor controlled and condition monitoring systems due to the wide usable frequency range and adaptability.

Due to their excellent properties like flexibility, anisotropy and long term stability Macro Fiber Composites (MFC) fit most of the requirements to meet the specifications of energy harvesting systems based on the piezo electric effect. A test set up for the introduction of uniform strain into the MFCs as well as an electrical impedance matching will be presented based on a general consideration about energy transfer in electric dipoles and a comparison between soft and hard piezo electric materials (PZT). Test results outlining the differences between a PZT-5A1 and a PZT-SP4 material particularly with respect to power output, electrical mismatching and long term stability will be discussed.

Finally examples of MFC based energy harvesting systems from different fields of application are presented, demonstrating the high potential of the MFC technology for the generation of electrical energy from mechanical vibrations. A short summary of the requirements for the electrical and mechanical subsystem concludes the presentation to help system engineers to design high performance energy harvesting systems.

TRACK 1: Energy Harvesting and Scavenging

7643-44, Session 5

Self-powered smart blade, part 1: helicopter blade energy harvesting

M. J. Bryant, A. Fang, E. Garcia, Cornell Univ. (United States)

A piezoelectric energy harvester driven by aeroelastic flutter vibrations has been designed to power embedded wireless sensors in a helicopter rotor. The nature of the rotor application makes using traditional hardwired sensing techniques difficult because slip ring systems are required to power and receive data from the sensors through the spinning hub. These difficulties make the rotor application well suited to a wireless sensing scheme that derives it power entirely from the operational environment.

The aeroelastic energy harvester consists of a piezoelectric beam cantilevered from the trailing edge of the rotor with a small plate attached to the tip of the beam by a flexible joint. Above a critical flow speed, a flutter instability occurs causing the plate to oscillate with coupled pitching and heaving vibrations. These flutter vibrations drive the tip of the beam, straining the piezoelectric layers and generating an electric current which can then be rectified and stored.

A system of coupled equations describing the structural, aerodynamic, and electromechanical aspects of the system are derived and presented. The model uses unsteady, nonlinear aerodynamics modeling to predict the aerodynamic forces and moments acting on the structure and to account for the effects of vortex shedding and dynamic stall. These nonlinear effects are included to predict the limit cycle behavior of the system over the range of wind speeds the device will experience in operation on the helicopter rotor application. In addition to the model predictions, wind tunnel test results for a prototype device will be presented and discussed.

7643-45, Session 5

Self-powered smart blade: helicopter blade power extraction and conditioning for on-blade RF wireless embedded sensor systems

A. Fang, M. J. Bryant, E. Garcia, Cornell Univ. (United States)

The paper focuses on evaluating how much power is available at the trailing edge of a helicopter blade at various lengths of the span and how the transformed energy can be manipulated into a stable power source for a self-contained wireless embedded sensing system. A novel aeroelastic piezo-electric energy harvester has been developed by the Laboratory for Intelligent Machines (LIMS) group at Cornell and it can be cantilevered off the trailing edge of a helicopter blade where the induced airflow due to the rotational motion of the blade excites the energy harvesting device. The current generated is passed through conditioning circuitry ultimately powering a Texas Instruments MSP430F2274 microcontroller, a MEMS accelerometer, and a CC2250 2.4 GHz RF wireless transceiver. A study of power consumption compared to varying duty cycle lengths is also performed. The results can be used to tune the design of the aeroelastic piezo-electric energy harvesting device for maximum performance.

7643-46, Session 5

Dynamic analysis of a structure integrated with periodically arranged piezoelectric transducers

Y. Lu, J. Tang, Univ. of Connecticut (United States)

In various engineering applications piezoelectric transducers have been used as actuators and/or sensors. When placed in a spatially periodic pattern, multiple transducers may exhibit unique characteristics which could benefit certain applications, e.g., enhanced sensitivity in damage detection or increased energy conversion efficiency. In this paper, a transfer-matrix-based modeling technique is adopted in the analysis of a beam structure integrated with multiple, periodically arranged piezoelectric transducers and shunt circuits. The beam is divided into a number of elements, each represented by two state vectors at its both ends. Vertical displacement, angle of rotation, moment and shear force are included in the state vectors as variables. Based upon a chosen beam theory, e.g. Euler-Bernoulli theory, the transfer matrix relating adjacent state vectors can be derived by matrix manipulation. In addition, the electro-mechanical interaction between the piezoelectric transducers and the beam is also taken into account. The electric charge collected by a transducer results in a mechanical moment applying back to the beam. A point matrix is thus added to include the effects of such feedback. The transfer-matrix-based modeling method is validated by comparing its frequency response results with that of a widely used modal method. Strong correlation can be observed between the two. Since the transfer matrix by nature has the advantage on describing the state propagation within the structure, the derived method thus could facilitates analysis involving local dynamics. As an example we apply it to the case of energy harvesting from beam vibration by periodically arranged piezoelectric transducers together with shunt circuits. Our analysis shows the specific configuration in both electrical and mechanical phases leads to typical characteristics of periodic structure. By adjusting electrical components we can further tune the energy harvesting process.

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7643-47, Session 5

Vibro-impacting power harvester

S. D. Moss, I. G. Powlesland, S. C. Galea, Defence Science and Technology Organisation (Australia); G. P. Carman, Univ. of California, Los Angeles (United States)

The certification of retro-fitted structural health monitoring (SHM) systems for use on aircraft raises a number of challenges. One critical issue is determining the optimal means of supplying power to the systems, given that access to existing aircraft power-system is unlikely to be permitted. Other conventional options such as primary and secondary cells can be difficult to certify and would need periodic replacement or re-charging, which in an aircraft context would pose a serious maintenance issue. Previously, the DSTO has shown that a structural-strain based energy harvesting approach can be used to power a device for SHM of aircraft structure [1]. Acceleration based power harvesting from airframes is more demanding (than a strain based approach) since the vibration spectrum of an aircraft structure varies dynamically with flight conditions, and hence a frequency agile or (relatively) broadband device is required to maximize the energy harvested. This paper will discuss the modelling and experimental validation of a novel power harvesting technique that utilizes the vibro-impact mechanism to harvest milli-Watts of power from RMS 400 milli-g mechanical vibrations of frequency 29-39 Hz, using a 49 gram flying mass.

[1] S. C. Galea, S. van der Velden, S. Moss, I. Powlesland, “On the way to autonomy: the wireless-interrogated and self-powered ‘smart patch’ system,” Encyclopaedia of Structural Health Monitoring, 1st Ed., Vol. 3, Chpt. 76, pp.1329-1350, John Wiley & Sons, ISBN 978-0-470-05822-0, 2009

[TRACK 1: Energy Harvesting and Scavenging]

7643-48, Session 6

Design of energy harvesting systems for harnessing vibrational motion from land and air vehicles

A. M. Wickenheiser, E. Garcia, Cornell Univ. (United States)

In much of the vibration-based energy harvesting literature, devices are modeled, designed, and tested for dissipating energy across a resistive load at a single base excitation frequency. This paper presents several practical scenarios germane to tracking, sensing, and wireless communication on land and air vehicles. Measured vibrational data from these platforms are used to provide a time-varying, broadband input to the energy harvesting system and are recreated in a laboratory setting for experimental design verification. Several circuit topologies are compared, including a simple resistive load (to provide a baseline), a passive rectifier circuit, and active, switching methods. Under various size and mass constraints, the optimal design is presented for each of the aforementioned circuit topologies, and an estimation of the maximum average power harvested under ideal conditions is given. Subsequently, the inefficiencies due to mechanical damping, circuit quality factor, rectifier losses, and active component power consumption are discussed. Finally, power management issues are considered in the design of a circuit for intermittent power expenditure in the presence of low levels of available energy.

7643-49, Session 6

An efficiency analysis of a novel thermal energy harvesting device

S. M. Sandoval, C. Hsu, G. P. Carman, Univ. of California, Los Angeles (United States)

A model of efficiency for a unique thermal energy harvesting device is developed, which predicts an upper-bound relative efficiency of 30%. This unique device is based on the coupling between magnetic and thermal energy within a soft ferromagnetic working body. While in operation, the working body of this device is thermally cycled about its Curie point, such that its magnetic susceptibility is also cycled at the same frequency. The resulting phenomenon is a periodic magnetic force of attraction between the working body and a permanent magnet. The developed model quantifies the efficiency of thermal-to-magnetic energy conversion in this device. This model is based on previous theories of efficiency for thermomagnetic generators; however, modifications to these theories were made in order to match the expected physical states of this cycle. An upper-bound relative efficiency is calculated by assuming a perfect single-domain structure, whose spontaneous magnetization is described by Brillouin’s function. This idealized system assumes gadolinium as the working body, and operates at room temperature between a ΔT of 5 K. A basic schematic of a regenerative cascade cycle design is provided to show that a much larger ΔT can be achieved.

7643-50, Session 6

Feasibility of a multidimensional wave energy harvester

S. Behrens, A. Fowler, Commonwealth Scientific and Industrial Research Organisation (Australia)

A typical limitation of current wave energy harvesters is that they often harvest energy in only one degree of freedom, e.g. from the heaving motion of the waves. Hence, wave motions in additional degrees of freedom such as swaying, pitching and rolling are unutilised. This problem may be addressed by developing a multi-dimensional wave energy harvester which is able to capture the unutilised wave energy using six degrees of freedom.

The multidimensional wave energy harvester design consists of a watertight frame, with a proof mass suspended within the centre of the frame via elastic supports. The motion of the mass is used to generate electrical power through a number of transducers, which are placed in parallel with each element of the suspension system. By placing a load impedance across the terminals of each transducer, electrical power can be extracted from the device. Thus, wave motions along any translational or rotational axis will result in the generation of electrical power through the inertia of the mass and the transducer elements.

A Simulink/SimMechanics model of the multidimensional wave energy harvester has been developed. A preliminary simulation of the performance of the harvester using recorded wave data has resulted in an average power output of 127mW, confirming the initial feasibility of the design and encouraging further investigation into the concept; further wave data including both translational and rotational wave motions will be captured in order to guide the further development of the design. The paper will report on the performance of a physical version of the final design, and hence evaluate the feasibility of the multidimensional wave energy harvester.

TRACK 1: Energy Harvesting and Scavenging.

7643-51, Session 6

Thermoelectric energy harvesting as a wireless sensor node power source

C. G. Knight, Commonwealth Scientific and Industrial Research Organisation (Australia); J. P. Davidson, James Cook Univ. (Australia)

Size and power requirements of wireless computing and mobile devices are decreasing and this has allowed data collection across a range of spatial and temporal ranges. These devices have power requirements that often necessitate batteries as a power source. As the power requirements decrease, alternative energy sources become available.

Thermal energy requires a higher temperature source and a lower temperature sink. Energy is extracted as heat flows from the hot side to the cold side. The magnitude of the difference between the source and

sink determines both the efficiency and rate at which the energy can be extracted.

A device has been designed and tested to exploit the temperature difference between a sun warmed plate and a heat sink immersed in water. The concept uses a solid-state thermoelectric device to extract electrical power from the heat flow. Theoretical estimations of power available from measured temperature differences are compared with the results of the designed device. Experiments were completed at a variety of winter time, environmentally available temperature differences with power outputs of 50mW achieved with rudimentary devices. The air to water temperature gradients were typically below 10K. Results indicate that maximum power output approached 2.5% of the predicted Carnot limit.

The results show that such a system could power a wireless node continuously in areas where a source of thermal energy is available. We are currently in the process of powering a CSIRO Fleck wireless node to transmit temperature and battery voltage at regular intervals throughout the day.

7643-52, Session 6

Theoretical analysis of acceleration measurements in a model of an operating wind turbine

J. White, Purdue Univ. (United States)

Wind loading from turbulence and gusts can cause damage in horizontal axis wind turbines. These unsteady loads and the resulting damage initiation and propagation are difficult to predict. Unsteady loads enter at the rotor and are transmitted to the drivetrain. The current generation of wind turbine has drivetrain-mounted vibration and bearing temperature sensors, a nacelle-mounted inertial measurement unit, and a nacelle-mounted anemometer and wind vane. Some advanced wind turbines are also equipped with strain measurements at the root of the rotor. This paper analyzes additional measurements in a rotor blade to investigate the complexity of these unsteady loads. By identifying the spatial distribution, amplitude, and frequency bandwidth of these loads, design improvements could be facilitated to reduce uncertainties in reliability predictions. In addition, dynamic load estimates could be used in the future to control high-bandwdith aerodynamic actuators distributed along the rotor blade to reduce the saturation of slower pitch actuators currently used for wind turbine blades. Local acceleration measurements are made along a rotor blade to infer operational rotor states including deflection and dynamic modal contributions. Previous work has demonstrated that acceleration measurements can be experimentally acquired on an operating wind turbine. Simulations on simplified rotor blades have also been used to demonstrate that mean blade loading can be estimated based on deflection estimates. To successfully apply accelerometers in wind turbine applications for load identification, the spectral and spatial characteristics of each excitation source must be understood so that the total acceleration measurement can be decomposed into contributions from each source. To demonstrate the decomposition of acceleration measurements in conjunction with load estimation methods, a flexible body model has been created with MSC.ADAMS©. The benefit of using a simulation model as opposed to a physical experiment to examine the merits of acceleration-based load identification methods is that models of the structural dynamics and aerodynamics enable one to compare estimates of the deflection and loading with actual values. Realistic wind conditions are applied to the rotor blade with virtual accelerometers installed along the rotor blade. The accuracy of the acceleration decomposition methods will be compared to the actual modeled sources of acceleration for verification of the data analysis algorithms. Furthermore, the deflection and load estimates will also be compared with the true loads. Verification of acceleration decomposition and loading estimation is critical in developing confidence and insight before analyzing turbine operational data.

7643-53, Session 6

Study of underwater performance of solar cells with change in depth and salinity

K. Joshi, S. Priya, Virginia Polytechnic Institute and State Univ. (United States)

There's lot of interest in scientific community in harvesting Ocean energy. Especially for use of underwater surveillance vehicles to serve their energy needs without depending on battery or external sources. Solar cells can be used as the source of power on board for these vehicles. Since these vehicles are working under ocean waters and may need to dive at various depths need was identified to evaluate performance of solar cells at various depth and various salinity levels observed in the ocean. This work presents results of experimental investigation of the performance of solar-cell as the parameters depth from surface and salinity level varies.

7643-102, Poster Session

Implement trigger for a NI data acquisition card PCI 5105 in the measurement studio development environment for a high speed demodulator based on fiber Fabry-Pérot tunable filter (FFP-TF)

H. Zhang, Stevens Institute of Technology (United States); S. Yang, Yantai Univ. (China); L. Fan, P. Wang, Stevens Institute of Technology (United States); X. Zhao, Z. Wang, Yantai Univ. (China); H. Cui, Stevens Institute of Technology (United States)

A NI (National Instruments) high-density data acquisition card PCI 5105 is installed in a high speed demodulator based on Fiber Fabry-Pérot Tunable Filter (FFP-TF) for Weigh-In-Motion (WIM) system. The instability of spectra of fiber Bragg grating (FBG) sensors caused by intrinsic drifts of FFP-TF needs a suitable trigger time obtained by a trial-and-error method. However, the driver of PCI 5105 in Measurement Studio development environment does not provide analog trigger type but only digital trigger type. In latter mode, only two choices, rising or falling edge trigger, can be chosen and the trigger time is not flexible any more. Moreover, the high level of original trigger signal chosen from tuning voltage of FFP-TF is dramatically larger than the maximum input overload voltage of PCI 5105 card. To resolve this incompatibility, a scheme of low-cost, easy-to-install differential electrical converter to change analog trigger signal into digital trigger signal is presented. The obtained results of frequency response about this converter clearly demonstrate that this method is effective when the frequency of trigger signal is less than 3,000 Hz. This converter can satisfy current requirement of this kind of demodulation, since mostly actual working scanning frequency of FFP-TF is less than 1,000 Hz. This method may be recommended to resolve similar problems for other NI customers who have developed their data acquisition system based on Measurement Studio.

7643-103, Poster Session

Shake table tests of semi-active fuzzy control for seismic response reduction with piezoelectric friction damper

D. Zhao, Yanshan Univ. (China) and Dalian Univ. of Technology (China); H. Li, Dalian Univ. of Technology (China)

The seismic reduction of the semi-active fuzzy control system including a new type of piezoelectric friction damper and fuzzy controller is investigated on the MTS shake table using a two-storey steel structure under various earthquake records. The hysteresis performance of the damper under linear increased voltage is tested on MTS in advance. The force generation of the actuator in the damper under

different preload is also tested before the implementation of the shake table test. The relationship between force generation and voltage is nearly linear. The preload force acted on the damper is determined by nonlinear time-history analysis under normal earthquakes. The semi-active fuzzy control algorithm is used to adjust the voltage of the piezoelectric actuator according to the structure response. This method has benefit to produce required voltage to be input to the damper so that the desired force can be produced and thus decrease the structure responses. The implementation of the control algorithm is used in dSPACE by SIMULINK. The seismic reduction of the control algorithm is investigated under several earthquakes. Experimental results indicate that the proposed semi-active fuzzy control system consisting of a T-S fuzzy controller and piezoelectric friction damper can be efficient in reducing the inter-storey drifts and acceleration under earthquake excitations.

7643-104, Poster Session

Multimodal vibration control of a plant using synchronized switch damping based on negative capacitance

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In this article, a new semi-active SSD (Synchronized Switch Damping) approach based on negative capacitor is proposed and applied to the multimodal vibration control of a beam. A negative capacitance is designed to substitute the inductor in the classical switched shunt circuit of SSD control. Due to special properties of negative capacitance, switched discharging of the piezoelectric element can induce voltage inversion on it. The switched voltage on the piezoelectric element under steady state depends on the ratio of the capacitance of the piezoelectric and the negative capacitance. The switch control strategy based on negative captitance is the same with the classical SSD method based on inductor. In single mode vibration control using SSD approach, optimal control performance is obtained when the voltage on the piezoelectric actuator is switched at each extremum of displacement. Experimental results showed that better control performance can be achieved if switching actions are skipped at some of the extrema in multi-mode control. Hence the switch control strategy is the most important issue in the application of SSD approaches in multi-mode vibration control. In this study, the fundamental theory of optimal switch control in SSD approaches for multi-mode vibration control is investigated. The new SSD method based on a negative capacitance has been applied to the multimodal vibration control of a plant and its control results were compared with those of previously developed SSD techniques using inductance. Very good control performance was achieved using the new switched shunt circuit.

7643-105, Poster Session

Active unbalance control in an asymmetrical rotor system using a suspension with linear actuators

M. Arias-Montiel, G. Silva-Navarro, Ctr. de Investigación y de Estudios Avanzados (Mexico)

This work deals with the problem of the active unbalance control in an asymmetrical rotor-bearing system with two disks supported by an active suspension based on two lateral linear actuators. For the analysis and control synthesis a mathematical model is developed using Finite Element Methods (FEM). A linear quadratic regulator (LQR) is applied in order to minimize the displacements of the two disks by means of the application of an active bearing with control forces provided by an arrangement of two linear actuators. The control scheme is designed to attenuate the overall system response in the natural frequencies (resonances), taking into account the unbalance response associated to both disks and shaft and, hence, controlling the system performance during the first modes. To do this, a Luenberger type observer is used to estimate those not measurable states from the displacements in only one shaft point and, therefore, making possible the synthesis of an optimal LQR control based on the estimated state feedback. The control forces obtained from LQR control are introduced to mathematical model of actuators and taking into account their dynamics, we get the voltages input necessary to provide the unbalance compensation forces. The proposed control scheme is proved by numerical results and then, validated experimentally on a test rig which was designed and constructed. Numerical and experimental results show significant reductions in the unbalance response of the overall system.

7643-108, Poster Session

Ultrasonic piezoelectric cleaning of acoustic vector sensing elements

S. Cravens, R. M. Barrett, The Univ. of Kansas (United States)

The Microflown is an acoustic vector sensor that utilizes two small diameter filaments to determine particle velocity incited by a sound source. This technology is presently employed in several applications including acoustic holography and determination of “noisy” components in automobiles and machinery. These applications are found in clean environments where there is little risk of environmental fouling of the sensor. However, there are a wide variety of applications for this device that require the ability to clean debris from the Microflown filaments. This debris consists of environmental agents including but not limited to dust, pollen and water. This is problematic because the Microflown operates on similar principles to hot wire anemometry which means a small particle which covers even a small portion of one of the filaments renders the sensor essentially useless.

This paper presents an investigation into the effects of environmental debris on the sensitivity of a hot wire anemometer. A method of cleaning the unwanted particles from the sensor using piezoelectric actuators, excited at ultrasonic frequencies is also presented. To simulate a Microflown sensor, a boron fiber has been dusted and then shaken using a piezoelectric actuator. The dust particles were successfully removed from the fiber at a frequency of approximately 20 kHz.

7643-109, Poster Session

Feasibility study on self-powered active vibration control using a piezoelectric actuator

K. Nakano, M. Ohori, A. Tagaya, The Univ. of Tokyo (Japan)

A self-powered active vibration control is a system that produces a control force using energy generated from vibration and carries out the control without power sources. In previous study, the self-powered active vibration control was achieved using an electromagnetic actuator and its suppression performance and power balance between the consumed and the generated energy were examined.

However, in the field of smart structures, a piezoelectric transducer is a major actuator. Since it is light and responses quickly, it is suitable for an actuator of a distributed control system. As many actuators are utilized in this system, many power sources, sensors and wires are needed, which makes the hardware very complex.

Then the author proposes to realize the self-powered active vibration control using a piezoelectric actuator. It is quite different from an electromagnetic actuator, since it produces force from electric charge, while mechanical deflection induces voltage. An equation to estimate the power generated by the piezoelectric transducer is derived and the feasibility is examined through a power balance analysis. The results of the numerical simulations and experiments show the proposed system can achieve active vibration control under the condition where the generated energy exceeds the consumed energy.

Conf. 7643: Active and Passive Smart Structures and Integrated Systems IV

7643-110, Poster Session

Piezoelectric energy harvester operating in flowing water

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The first piezoelectric energy harvesting device is presented which converts energy out of laminar flowing water without any rotating parts and hereby scalable to micrometer dimension.

The harvester converts the energy out of the bending of a piezoelectric bimorph cantilever. The body disturbs the laminar flow and the consequences are vortexes behind it in flow direction. This effect caused by the bluff body is called “von Kármán’s vortex street”. Thus with the cantilever fixed behind the bluff body the vortexes cause alternating pressure differences above and beneath the cantilever and as a result the cantilever starts to bend up and down. The bimorph now oscillates in a media depending resonance frequency.

A macroscopic model of this harvester was build consisting of nine piezoelectric bimorph modules in a dimension of L x W x T = 20mm x 12mm x 0.35mm with two active piezoelectric layers each.

Earlier measurements of the bimorphs in the wind channel proved the working principle. The open-circuit voltage generated by the cantilever was investigated at flow velocities between 4.5m/s and 45m/s. The produced voltage shows strong coupling with the velocity and also the position of the cantilever relating to the others affects it.

First measurements in the water channel at velocities between 0.2 m/s and 0.9 m/s showed a similar behavior as in air. Due to the much higher density of water the reachable velocity is quite lower than in air. However, with the energy density in water is quite higher than in air the power generation is much better also at lower velocities.

The voltage generated of one cantilever rises almost exponentially with velocity. For the comparison of the values gained in water and air they are converted to the same velocity. Assuming an exponential increase the generated effective voltage in water at 2.0m/s is approximately 300mV which is compared to the value in air (10mV) about 30 times higher.

An effect that was considered in flowing water is the self-synchronization of the modules arranged horizontally in a row.

To make the power usable generated by the oscillating bimorph a low-power circuitry was build up. The circuitry consists of a center-tapped rectifier with capacitors for energy storage and a low-power logic part consisting of an analog switch, transistors and resistors. The circuitry is controlled by itself by designing the electronic devices matching to the proper value. The system gives energy to the load if the voltage applied to the capacitors reaches a predefined value. The release of the energy happens stochastically because the analog switch is only controlled by the applied voltage level.

If a time-controlled activation of the load is needed the circuitry can be extended with a monostable flip-flop which controls the analog switch.

The system was characterized and optimized in the wind channel at a velocity of 8.0m/s. The model was able to supply the load with approximately 2mW in an average time interval of 760ms.

The introduced system offers new possibilities for converting energy of flowing water using microstructured devices in conjunction with a relatively easy circuitry.

TRACK 1: Energy Harvesting and Scavenging

7643-111, Poster Session

Manufacture of active piezoelectric components using plastic injection molding

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Multifunctionality of smart structures combining conventional structures with active materials has been demonstrated on laboratory scale worldwide. Until now, large scale production of such systems are limited by the deficit of applicable series technologies and the considerable expenditure to mount a lot of damageable components.

It was an objective of the present project to develop a technology for the manufacture of active compound structures that combines the assembly of semi finished products and compound manufacturing in one single step. Semi-finished products may be piezoelectric actuators or sensors, clamping elements, joints, mechanical and electrical connections and electronic circuits, for examples.

A possible approach for a batch production of such active structural components is to use injection molding. This was demonstrated using the example of a compound actuator with integrated stress-strain transformation. Such devices can be used in mechatronic machine components. The compound actuator, according to our design, comprises two stack actuators, mechanical and electrical connections and prestressing elements within one injection molded matrix.

Design sketch, simulation, actuator design and fabrication technology are described in this paper. The approach can be used in all technical fields where active structural components are applicable.

The results of this project are based on the cooperation of several institutes of the Fraunhofer-Gesellschaft in Germany.

7643-112, Poster Session

Characterization of multifunctional piezoelectric fibers as structural capacitors for energy storage

J. W. Shaffer, Y. Lin, H. A. Sodano, Arizona State Univ. (United States)

Multifunctional composites are structural materials that can carry external loads as well as provide an additional performance related functionality. This additional functionality could include vibration control, sensing and actuation, and energy generation and storage. Interest in these composites is derived from the increase in safety and performance, with minimal gain in complexity, they can provide to a system. For instance, in unmanned air vehicles (UAVs), soldier systems, and space structures where weight and energy consumption often dominate the structural design, multifunctional materials can improve system efficiency by incorporating energy harvesting or storage components with the structural elements. The concept of utilizing the structure as a source of energy has been investigated by several researchers. Neudecker et al. (2003) developed a fiber based Li-ion battery for integration into composites. Electrostatic capacitors have also been studied; however they primarily utilize the addition of a dielectric powder to the matrix which results in very low performance. Lin and Sodano (2009) performed one study that achieved equal energy density to commercial ceramic capacitors by coating a SiC fiber with a BaTiO3 layer. The core fiber provided strength and flexibility, but its conductivity also allowed it to act as an electrode. While this design proved effective for energy storage, the fiber diameter (140 m) is generally too large to be effectively incorporated into a carbon fiber reinforced composite. To address this issue a novel thin film deposition technique will be developed to coat carbon fibers with lead zirconate titanate (PZT). Cathodic electrolytic deposition will be used which allows the individual carbon fibers to be coated while in the tow. The deposition process will be characterized, and methodologies to obtain crack-free coatings will be explored. Carbon fibers have been widely used as composite reinforcements due to their exceptional mechanical properties, and PZT has been extensively studied because of its very high electromechanical coupling and dielectric coefficients. Therefore, the resulting multifunctional fiber could have excellent mechanical, piezoelectric, and dielectric properties. This multifunctional fiber can convert mechanical energy to electrical energy, which in turn can be stored for use by other electrical devices. This paper will discuss the characterization of the energy storage capabilities of the PZT multifunctional fiber by comparing experimental results to theoretical expressions derived from Gauss’s Law for cylindrical capacitors. Energy densities of different PZT coating thickness samples are

characterized by testing their capacitance and breakdown voltage. The coating thickness that provides the maximal energy storage capacity will be determined by comparing the energy densities and the results will show that the energy density of this novel multifunctional fiber is significantly higher than previously developed structural capacitors.

TRACK 1: Energy Harvesting and Scavenging

7643-113, Poster Session

Damping capacity in shape memory alloy honeycomb structures

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SMA honeycombs have been recently developed by several Authors [1, 2] as innovative cellular structures with self-healing capability following mechanical indentation, unusual deformation (negative Poisson's ratio [3]), and possible enhanced damping capacity due to the natural vibration dissipation characteristics of SMAs under pseudoelastic and superelastic regime. In this work we describe the nonlinear damping effects of novel shape memory alloy honeycomb assemblies subjected to combined mechanical sinusoidal and thermal loading. The SMA honeycomb structures made with Ni48Ti46Cu6 are designed with single and two-phase polymeric components (epoxy), to enhance the damping characteristics of the base SMA for higher-frequency vibration. The unit cells are represented by FE models using pseudo-elastic and superelastic material laws, and used to extract parametric design surfaces of the stiffness and hysteresis versus the geometric parameters of the honeycomb topology (Figure 1). Assemblies of composite SMA unit cells are manufactured using ribbons curved in a OX-shape mould, some of which are connected by an interlayer of epoxy, and tested under uniaxial dynamic mechanical loading. General good agreement has been recorded between the experimental results and the numerical simulations related to the single phase SMA honeycomb (Figure 2), with the two-phase cellular structures showing a definite trend in terms of enhanced damping capacity.

7643-114, Poster Session

Small-scale modular wind turbine

C. Vernier, S. Bressers, Virginia Polytechnic Institute and State Univ. (United States)

This paper reports the fabrication and characterization of a horizontal-axis, small-scale modular windmill that is capable of charging small electronic devices such as cell phone and powering a remote sensor network. The design criteria for the windmill included (i) portability, which implies that windmill was modular in architecture allowing on-site assembly in few minutes, (ii) packaging, which implies that windmill can be carried in a bottle of volume 2.49 liters and bottle itself became the base stand, and (iii) low start-up wind speed. The turbine was designed to operate in the wind speed range of 5 to 12 mph. It was found that windmill can start at low wind speeds of 5.5 mph, and once started it was able to maintain sustainable rotation at 4.5 mph. Results are reported on selection of motor, blade design, turbine structure, and implementation of modularity. Performance characterization was conducted using a home-built low-speed wind tunnel. It was found that the fabricated windmill can generate 157 mW power at nominal wind speed of 8mph and 500mW power at peak wind speeds of 11 mph.

7643-116, Poster Session

Development and flight test of a shape memory alloy flight control system

M. T. Brennison, R. M. Barrett, The Univ. of Kansas (United States)

This paper chronicles an investigation of using shape memory alloys (SMA) to drive a flight control system. The paper begins discussing the development of SMA as well as well as aircraft applications. The paper continues with the physical properties of SMA and how to take advantage of these properties with an electric current. The paper then describes the development of the actuator as an antagonistic system utilizing a Wheatstone bridge with variable resistors to develop a closed loop feedback system. The paper proceeds to describe how a demodulator circuit from JR NES 911 subscale servoactuator was implemented so that the SMA actuator could interpret signals from a radio-control transmitter-receiver; as well as, diodes to control which SMA wire would be actuated depending on the signal voltage. The diodes were replaced with transistors as the power requirements of the SMA were increased and required a secondary power source for an airworthy actuator. The paper follows the prototype design with details of the test aircraft and operational procedures. During tests the actuator proved capable of 20 degrees of deflection in either direction as well as 7.5 oz*in of torque. The actuator was placed in a modified radio controlled sailplane of 78.5 inch span and was used to control the rudder. The aircraft was flown through maneuvers to demonstrate the actuator had sufficient rudder control in flight. The paper concludes stating the success of the actuator and for the first time, precise servo actuation using SMA was achieved and demonstrated.

7643-117, Poster Session

A comparative experimental study on structural and interface damping approaches for vibration suppression purposes

Y. Liu, ETH Zürich (Switzerland)

Dynamic loadings in automotive structures may lead to reduction of driving comfort and even to failure of the components. Damping treatments are applied in order to attenuate the vibrations and improve the long term fatigue behaviour of the structures. This experimental study is targeting applications in floor panels that are mounted to the load-carrying primary structure of the vehicle. The Objective is to reach outstanding damping performance considering the stringent weight and cost requirement in the automotive industry. An experimental setup has been developed and validated for the determination of the damping properties of structural specimens also considering interface damping effects.

This contribution is structured in three main parts: test rig design, experimental results and discussion. Reliable and easy-to-use devices for the characterization of the damping properties of specimens between 200X40 mm2 and 400X400 mm2 are not available "on the shelf". In this context, we present a flexible experimental set-up which has been realized to (1) support the development of novel damping solutions for multi-functional composite structures, (2) characterize the loss-factor of the different damping concepts, including boundary effects, and (3) validate in-house developed simulation tools. A variety of novel passive and active damping treatments have been investigated including viscoelastic, coulomb, magnetorheological (MR), particle, magnetic and eddy current damping. The particle, interface as well as active damping systems show promising performance in comparison to the classical viscoelastic treatments.

7643-118, Poster Session

Suspension system with magneto-rheological damper and energy regeneration

Z. Wang, Z. Chen, Hunan Univ. (China)

Semi-active control systems are becoming more and popular because they offer both the reliability of passive systems and the versatility of active control without large power demands. In particular, magnetorheological (MR) dampers have received great attention from the community. However, the systems based on MR damper still require external power supply. Harvesting energy from structural vibration is quite a new and challenging research field. One potential

application of energy harvesting is to provide power for a control system. Therefore, a new suspension system with MR damper and energy regeneration is presented. The system includes four key parts: a rack and pinion gearing, a permanent magnet direct-current (DC) generator, a current-adjusted MR damper, and a control circuit. The system can work in two different modes that are passive or semi-active according to the complexity of the control circuit. In the semi-active mode, the sky-hook control method is adopted. The system is embedded with a quarter-car model to control the vibration of suspension system. Random and bump excitations are considered to test the suspension system and investigate its performance. Simulation results have showed the feasibility and effectiveness of proposed new vehicle suspension system in this paper.

7643-119, Poster Session

Harvesting energy using a piezo-composite generating element (PCGE)

C. M. T. Tien, N. Goo, Konkuk Univ. (Korea, Republic of)

Energy can be reclaimed and stored for later use to recharge a battery or power a device through a process called energy harvesting. Piezoelectric is being widely investigated for use in harvesting energy from motion such as body movement and machine vibration. This paper presents a simple analytical model to describe output voltage effectiveness of a Piezo-Composite Generating Element (PCGE) from vibration and its experimental verification. PCGE is composed of layers of carbon/epoxy, PZT ceramic and glass/epoxy. During the manufacturing process, the stacked layers were cured at an elevated temperature of 177 Celsius Degrees in an autoclave, which made the PCGE pre-stressed due to a mismatch in the coefficients of thermal expansion between the constituent layers. The effect of the pre-stressed on the performance of output voltage therefore was studied. For the experiments, three kinds of lay-up configurations of PCGE were utilized to verify the model and to approve its ability to convert oscillatory mechanical energy into electrical energy. The predicted performances are much in agreement with experimental ones.

7643-120, Poster Session

The disadvantage effect of magnetorheological damper on the hosting structures

X. Li, Sr., Shandong Jianzhu Univ. (China); H. Li, Dalian Univ. of Technology (China)

Magnetorheological (MR) damper is a kind of semi-active control device that uses MR fluid to provide controllable damper by adjusting its parameters according to the instantaneous response of the hosting structures, which is quite promising for civil engineering applications. The aseismic reinforcement of the structures is a widely used engineering technology. In the paper, the method of reinforcing aseismic structures by MR damper is presented.

Firstly, the experiment system of a three-floor reinforced concrete frame-shear wall eccentric structure has been built based on Matlab/Simulink software environment and hardware/software resources of dSPACE.

And then a shaking table test for the hosting structure with and without MR dampers is implemented subjected to three different ground motions using rapid control prototyping (RCP) technology. Due to FBG's superior ability of explosion proof, immunity to electromagnetic interference and high accuracy, especially fitting for measurement applications in harsh environment, the FBG strain sensors were used in this experiment for forces measurement of the columns. The experimental results show that the coupled translation and torsion responses are significantly mitigated by MR dampers. Unfortunately, the experimental results also show that the increase on axial force of the column was discovered due to MR dampers fitted in the hosting structure.

Finally, calculated and verified methods about the axial force of the column with and without MR dampers were presented in the paper. Simulated example gave an explanation on the influence of column on the MR damper structure.

7643-121, Poster Session

A novel above-knee prosthetic knee based on magnetorheological effect: design and testing

D. Wang, L. Xu, Chongqing Univ. (China)

In this paper, the principle and structure of an integrated above-knee prosthetic mechanism based on four-bar linkage and magnetorheological (MR) effect are proposed and realized to imitate the instant center of rotation of knee joint accurately and the controllable bending moment. In the developed integrated above-knee prosthetic knee, the four-bar linkage is designed according to human body kinematics and dynamics, and the up and below links of the four-bar linkage are connected with the piston rod and cylinder of the MR fluid damper, respectively. The control for the MR fluid is realized with the fluid gaps in the piston of the MR fluid damper, which will simplify the structure of the cylinder and will be beneficial to the material selection of the cylinder. According to the proposed principle and realized structure, a polycentric above-knee prosthetic knee mechanism based on MR effect is designed and fabricated. The characteristics of the developed above-knee prosthetic knee mechanism based on the MR effect, including the controllable damping ratio and motion accuracy, are tested. The research results indicate that the developed integrated above-knee prosthetic knee mechanism possesses the following advantages: (1) the structural integration is skillfully achieved, through which the structure can be simplified and the installation space and weight can be saved, (2) the instant center of rotation of normal human being can be imitated accurately, and (3) the bending moment of the developed integrated above-knee prosthetic knee mechanism can be continuously changed with a short response time and large controllable damping ratio.

(SSN03/Track 4: Magneto Rheological Systems)

7643-122, Poster Session

Performance optimization of an integrated relative displacement self-sensing magnetorheological damper

D. Wang, X. Bai, Chongqing Univ. (China)

In order to let magnetorheological (MR) dampers move into the industrial marketplace, Wang and Wang (Smart Materials & Structures 2009 18 095025) proposed and explored an integrated relative displacement sensor (IRDS) technology to make MR dampers self-sensing based on electromagnetic induction and the principle of an integrated relative displacement self-sensing MR Damper (IRDSMRD) based on the IRDS technology. Although the function of the relative displacement sensing property can be integrated into MR dampers and the designed IRDSMRD possesses the large controllable damping ratio and the good relative displacement sensing performance utilizing the IRDS technology, in order to integrate the IRDS into the MR damper, the damping performance of the IRDSMRD will definitely influence its sensing performance and vice versa. In order to maximize the performance of the IRDSMRD, including decreasing the nonlinearity of the IRDS, the damping performance and sensing performance of the IRDSMRD should be compromised carefully, which needs to be realized by performance optimization. In this paper, the optimization method to optimize the performance of the IRDSMRD, including the performance of the damping force and the performance of the IRDS of the IRDSMRD, is proposed and realized based on the finite element analyzing results and experimental results of the IRDSMRD. In order to realize the performance optimization of the IRDSMRD, the performance index is determined by the weighted function of the reciprocal value of

the damping force and the nonlinearity of the IRDS. The constrained optimization problem is solved to minimize the performance index. The optimized results are validated by finite element analyzing results and experimental results, which indicate that the sensing performance and damping performance of the IRDSMRD can be compromised through the optimization method. (SSN03/Track 8: Modeling, Simulation, Optimization, Signal Processing, Control, and Design of Integrated Systems)

7643-123, Poster Session

BATMAV: a 2-DOF bio-inspired flapping flight platform

G. Bunget, P. Cook, S. S. Seelecke, North Carolina State Univ. (United States)

The overall objective of the BATMAV project is the development of a biologically-inspired Micro-Aerial Vehicle for flapping flight. While flapping flight in MAV has been previously studied, this paper presents a platform that features bat-inspired wings able to actively fold their elbow joints and passively their wrist joints. The wings are assembled through superelastic SMA joints and are actuated by SMA 'muscle' wires that mimic the pectoral and biceps of the natural bat flier. These 'muscle-wires' exhibit actuation frequencies of 10Hz corresponding to the range of bat flapping frequencies. Aerodynamic parameters like flapping frequency, lift and thrust are studied and compared with a kinematic model and with the aerodynamics of the natural flier.

7643-124, Poster Session

FE analysis of SMA-based dual-joint flexible nozzle used in smart inhaler system

N. Lewis, S. S. Seelecke, North Carolina State Univ. (United States)

Recently, a novel patent-pending Smart Inhaler system has been developed at NC State University [1]. The Smart Inhaler design concept has the potential to improve pulmonary ailment treatment by targeting the delivery of inhaled aerosol medication to specific locations within the human lung [2]. This targeted delivery will reduce the amount of healthy lung tissue exposed to potentially harmful medications and enable new oral uptake methods for, e.g., lung cancer treatment. However, controlled delivery can only be accomplished if the medication is injected into an inhaled stream of properly conditioned laminar flow from a precise location. In particular, the medication must be injected into the inhaled flow using a small nozzle that can be positioned without disturbing the flow. This paper presents a finite element analysis (FEA) for a dual-joint flexible nozzle used in the Smart Inhaler design. The nozzle uses shape memory alloy (SMA) wires for their unique dual sensing and actuating capabilities. The FEA program ABAQUS was chosen to model the Smart Inhaler system because of its effectiveness in modeling materials with non-linear behavior and its widespread commercial availability. The SMA wires were modeled using a mesoscopic free energy model for SMA behavior [3] and implemented in ABAQUS together with the Smart Inhaler nozzle. For each wire actuation, the required voltage, corresponding heat input, and the resulting forces on each SMA wire were determined together with the electric resistance change, and the position of the nozzle tip was mapped. The results from the simulation were validated against measurements taken with the Smart Inhaler prototype using a video camera system and the LabVIEW Machine Vision software by National Instruments. Using SMA actuator wire models in ABAQUS will help optimize the Smart Inhaler design and assist in the development of other SMA wire-actuated projects in the future.

[1] Pausley, M. and Seelecke, S., "Multifunctional SMA-based Smart Inhaler System for Improved Aerosol Drug Delivery -Design And Fabrication," Proceedings of SPIE, the International Society for Optical Engineering, 10-13 March, 2008, San Diego, California, USA.

[2] Kleinstreuer, C. and Zhang, Z., "Targeted drug aerosol deposition analysis for a four-generation lung airway model with hemispherical tumors," ASME Journal of Biomechanical Engineering, 197-206 (2003).

[3] Seelecke, S. and Muller I., "Shape memory alloy actuators in smart structures: Modeling and simulation," ASME Journal of Applied Mechanics, 23-46 (2004).

7643-127, Poster Session

Radar tower frequency control and earthquake response analysis

Z. Wu, Zhengzhou Univ. (China); Y. Li, North China Univ. of Water Conservancy and Electric Power (China); F. Wang, D. Wang, Zhengzhou Univ. (China)

In order to control floods, droughts and other natural disasters, the Chinese government decided to introduce the U.S. Doppler weather radar. For the sake of avoiding the impact of surrounding buildings on the radar, Radar Tower is usually higher, generally up to 100 meters. As the radar performance reasons, the required fundamental frequency of Radar Tower should not be less than 1Hz. For such a tall building, how to control the frequency of Radar Tower is an issue worth studying. Through a lot of calculation and analysis, research paper reached a number of increase natural vibration frequencies of laws: 1) Lowering center of gravity of the structure Lowering center of gravity can significantly improve the structural natural frequency. The two structures have the similar shapes, the lower center of gravity, the greater the frequency. 2) Setting leaning bracing Setting the leaning bracing is a very effective measure to improve the overall stiffness of the structure. Leaning bracing pivot height, leaning bracing and the ground level into a different angle, the influence on the overall stiffness of the structure is not the same. Pivot height is higher, making a greater contribution on the overall stiffness of the structure. When the angle between the leaning bracing and the Radar Tower increases, the structural stability enhances; bracing enlarging length, bar increasing flexibility and improving the frequency Radar Tower is little effect.

3) Reducing the mass concentration of the upper part of structure

Structure of the upper part, especially at the top of the mass of the structure, produces the natural frequencies of a greater impact. For the high-rise structure, reducing the mass at the top of the structure can be significantly improved natural frequency. 4) Increasing cross-section moment of inertia For the frame structure, increasing the beam and column cross-section size of the structure proceed to magnify the natural frequency. 5)Enlarging the thickness or number of shear walls For the frame - shear wall structure or wall structure, by increasing the number and thickness of shear walls is to improve the structure of the self-vibration frequency.

In the above structural frequencies adjustment method, increasing leaning bracing, and reducing the top mass of the structure are the most obvious effects of all. At the same time, paper also discusses on the Radar Tower of seismic response. Analyses of the methodology used for earthquake are response spectrum method, time history analysis method and random vibration analysis. Three methods of calculation results show that: Radar Tower performance is to meet China's seismic code to regulate internal force and displacement.

7643-54, Session 7a

Performance analysis of discrete whole-spacecraft vibration isolation platforms for flexible spacecrafts

B. Fang, Y. Zhang, Y. Li, Harbin Institute of Technology (China)

Abstract: The vibration environment of spacecrafts during launching is worse than that during its orbital movement. The whole-spacecraft vibration isolation technology can improve the dynamic environment of the spacecrafts. The whole-spacecraft vibration isolator is installed between the spacecraft and the rocket, with its stiffness and damping being the key components to achieve the vibration isolation. A number of researchers have investigated the whole-spacecraft vibration isolation based on rigid spacecrafts, but few have discussed flexible spacecrafts. In this paper, a disc-type discrete whole-spacecraft

vibration isolation platform with a new type of damping is adopted to study the vibration isolation performance of flexible spacecrafts. The isolator series with the cone shell adapter series. The damper of the platform consists of two rib plate and one viscoelastic layer, with the up-shear plate connected with the up-board of the isolator, the low-shear plate directly connected with the rocket. The dampers can offer maximal shearing forces. When the flexible spacecraft have longitudinal and lateral vibration, the viscoelastic dampers can offer vertical and horizontal shear damping forces. The dynamical equations of the whole-spacecraft vibration isolation system are established, and the transmissibility from bottom of the isolator to some key points on the flexible spacecraft is computed. The isolation performance of the vibration isolation coupling system for flexible spacecrafts is analyzed. Then, the isolation performance of the vibration isolation platform is investigated by vibration table experiment with sine sweep signals. The testing data for the flexible spacecrafts show that , in the frequency range from 10Hz to 150Hz, the vibration transmissibility at the first lateral natural frequency be decreased by 15%, and that by 40% at the second lateral natural frequency. The vibration transmissibility at the first longitudinal natural frequency be decreased by 10%, and that by 50% at the second longitudinal natural frequency. The analysis results and the testing data show that the discrete whole-spacecraft vibration isolation platforms have good isolation performance in wide frequency range to lateral and longitudinal vibration, and the vibration isolation platforms can be applied to flexible spacecrafts.

7643-55, Session 7a

Integration of adaptive components by incremental forming processes

M. Türk, P. Groche, Technische Univ. Darmstadt (Germany)

The Institute for Production Engineering and Forming Machines at the TU Darmstadt researches the reduction of uncertainty of bar structures by integrating adaptive components into the bars. As sensors, these components allow a monitoring of appearing loads, as actuators they allow an active influencing on appearing disturbances. Compared with conventional integration methods, which are usually differential methods like bolting or bonding, incremental forming processes appear particularly attractive for this task of integration. They feature the advantage that the forming of the parts as well as the integration of the active components can be realized in one process. On the other hand the forming and the local stresses are influenceable in wide ranges by the path of the tools. A large challenge with this kind of integration represents the sensitivity of the adaptronic components.

For a first estimation of the arising loads on the components which should be integrated, finite elements simulations of the integration process are accomplished. For this, a 3D-Modell of a spinning process is provided with the software Abaqus.

In this process, a ring is formed into the blank sheet by two steps. With this model an optimization of the tool path takes place regarding a minimization of the load of the component which should be integrated. At the same time it must be ensured that a safe load transmission between the ring and the blank sheet is ensured.

By following experimental tests, first parts with integrated passive rings could be produced. Despite the integration of the rings and the resultant cranks and undercuts it becomes a permanent compound.

An important aspect for resuming investigations is the experimental detection of the load, which affects the rings during the process. A direct interaction between the ring and the movement of the tool would be built by mounting a sensor system directly on the ring. By the exact determination of the forces on the ring during the forming process and the simultaneous, appropriate regulation of the infeed of the tool it would be possible to keep the load of the compound part within defined limits.

Another process to produce compound structures represents the rotary swaging. For this a design is generated, at which a ring-shaped component is integrated into a hollow bar. The joining procedure takes place via an infeed swaging process, whereby an axially form closure is produced. For the investigation of the arising loads during the process a finite element model is provided, too.

7643-56, Session 7a

Active sensor/actuator assemblies for vibration damping, compensation, measurement, and testing

V. M. Ryaboy, P. S. Kasturi, Newport Corp. (United States)

The vibration control module known as IQ damper® was introduced as part of active vibration damping system for optical tables and other precision vibration isolated platforms. Detailed description of the actively damped optical table (SmartTable®) was presented at the SPIE Smart Structures and Materials Symposium in 2005. The system damps natural vibrations of isolated platforms, and monitors the residual vibration in real time through analog and digital interfaces.

The paper describes steps to expand the application of these units to other tasks, namely, (1) dynamic testing of structures and (2) compensation of forced vibration in local areas. The sensor-actuator assemblies, including signal conditioning circuits, form compact dynamically symmetric modules with mechanical interfaces to an optical table.

In application to dynamic testing, the actuator is excited to generate the white noise, and the sensor signal is processed to calculate the dynamic compliance. The SmartTable controller is programmed to perform basic functions of a signal analyzer. The test data show that the vibration control modules can be used to measure dynamic compliance characteristics of optical tables with precision comparable to that of dedicated vibration measurement systems.

Vibration damping of most significant structural modes had been implemented using feedback controls of a small number of properly placed active dampers. However, this would not affect forced tonal vibration. The forced vibration may be caused, for example, by tonal disturbance at 60 Hz, 120 Hz, etc., from rotating electrical equipment nearby. In some practical situations, such tonal vibrations may be very visible or even dominating the vibration spectrum on the table surface. Current state of the art does not offer a practically feasible way to suppress all vibration, forced and normal, over the total table surface. However, by placing vibration control modules around a local area of the table supporting a vibration sensitive device, it is possible to abate forced tonal vibration in this area. MIMO and SISO algorithms of feedback control for vibration compensation will be discussed along with experiments demonstrating stable concerted work of several vibration control modules.

7643-57, Session 7a

Performance evaluation of energy recycling semi-active vibration suppression method with multiple piezoelectric transducers

S. Shimose, K. Minesugi, J. Onoda, Japan Aerospace Exploration Agency (Japan)

Study of the Energy Recycling Semi-active Vibration Suppression using piezoelectric transducers have performed by the author's group. In the proposal method, piezoelectric transducers are connected to the inductive switched shunt circuit, and it makes better use of counter electromotive force to suppress the vibration. We developed 1] a control method of selected modes in multiple modes, 2] a control method of self-sensing using a piezoelectric transducer also as a sensor and 3] an analog switching circuit of full self powered system. And we verified these methods by many experiments. Moreover we had applied this method to Actual Satellite Structural Model.

The results of experiments using this method showed that its performance was strongly dependent on how piezoelectric transducers were connected each other in series or in parallel. It is because the connection affects a frequency and total resistance of the shunt circuit.

We will report an evaluation of performance dependent on the connection of multiple piezoelectric transducers in this method.

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7643-58, Session 7a

Design of optimized piezoelectric HDD-sliders

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As storage data density in hard-disk drives (HDDs) increases for constant or miniaturizing sizes, precision positioning of HDD heads becomes a more relevant issue to ensure enormous amounts of data to be properly written and read. Since the traditional single-stage voice coil motor (VCM) cannot satisfy the positioning requirement of high-density tracks per inch (TPI) HDDs, dual-stage servo systems have been proposed to overcome this matter, by using VCMs to coarsely move the HDD head while piezoelectric actuators provides fine and fast positioning. Thus, the aim of this work is to apply topology optimization method (TOM) to design novel piezoelectric HDD heads, by finding optimal placement of base-plate and piezoelectric material to high precision positioning HDD heads. Topology optimization method is a structural optimization technique that combines the finite element method (FEM) with optimization algorithms. The laminated finite element employs the MITC (mixed interpolation of tensorial components) formulation to provide accurate and reliable results. The topology optimization uses a rational approximation of material properties to vary the material properties between 'void' and 'filled' portions. The design problem consists in generating optimal structures that provide maximal displacements, appropriate structural stiffness and resonance phenomena avoidance. The requirements are achieved by applying formulations to maximize displacements, minimize structural compliance and maximize resonance frequencies. This paper presents the implementation of the algorithms and show results to confirm the feasibility of this approach.

7643-59, Session 7a

Simultaneous thrust vector control and vibration isolation of satellites using steerable smart platforms

M. N. Ghasemi-Nejhad, K. Ma, Univ. of Hawai'i (United States)

This paper presents an innovative concept, control strategies and experimental verification of simultaneous thrust vector control and vibration isolation of satellites. First, the innovative concept is introduced by employing a smart platform as an active structural interface between the main thruster of a satellite and the satellite structure. Second, the inverse kinematics and singularity analysis of the smart platform are performed. Third, and control, thrust vector control model of satellites with smart platforms is deduced. Fourth, a multiple loop control strategy is proposed. It includes three cascaded feedback loops for nonlinear compensation of actuators, smart platform control and trust vector control, respectively, and a combined feedback-feedforward control scheme for vibration isolation. Finally, experiments are carried out and experimental results are illustrated and discussed. The cascaded multiple feedback loops compensate the hysteresis (for piezoelectric stacks inside the three linear actuators that individually have simultaneous precision positioning and vibration suppression), dead-zone, back-lash, and friction nonlinearities very well, and provide precision and quick smart platform control and satisfactory thrust vector control capability. The vibration controller isolates 97% of the vibration energy due to the thruster firing. The experimental results demonstrate that the simultaneous thrust vector control and vibration suppression is achieved with satisfactory performance.

7643-60, Session 7a

Design and manufacturing strategies for active tensegrity structures

N. Houle, K. W. Moored III, T. Kemp, H. Bart-Smith, Univ. of Virginia (United States)

Various actuation strategies for morphing tensegrity structures are explored. Two exciting solutions to the development of these active structures are "clustered" and "strut routed" actuation. Clustered actuation exploits the existence of cable elements in a tensegrity structure by allowing cables to be run over frictionless pulleys or through frictionless loops at the nodes. Strut routed actuation utilizes an active cable that is routed around the bar elements before connecting two nodes. Mechanics analysis to describe the actuation response will be presented. It has been shown that stable pre-stress states can be found under certain clustering patterns. This paper also presents the loading response of clustered and strut routed actuating tensegrity structures. An important aspect of this work is the development of robust manufacturing strategies for active tensegrity structures. Important considerations such as size scale, material selection, three dimensional limitations, and overall complexity must be considered when designing a structure that is to be constructed. Multiple connectivity schemes and actuation techniques are presented. Planar tensegrity beams have been fabricated that utilize both actuating strategies. Tests on these beams have been carried out to compare the loaded response with the analytical predictions.

7643-115, Session 7a

Review of smart material technologies for active parachute applications

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Parachutes are widely used for airdrop/aerial delivery of personnel and cargo. The performance (drag, lift, stability, etc.,) of a parachute is a function of the physical properties of the canopy fabric (such as porosity) and geometry of the canopy (such as air-vent openings). These variables typically remain constant during descent and therefore the parachute retains constant drag and lift. The ability to change these variables and the parachute drag and lift characteristics during flight in a controlled manner will greatly widen the performance envelope of a parachute and the maneuverability and versatility of the airdrop mission. In particular, it would be advantageous to design a parachute that descends swiftly but reduces its rate of descent as it approaches landing. By accomplishing this, the total time for an airdrop would be reduced, which would elevate the safety of personal and valuable cargo drop operations.

This paper provides a literature review of existing smart material technologies in an effort to improve the performance characteristics and enhance the safety of existing parachutes and parafoils. By harnessing the actuation abilities of smart materials, a change in the porosity or the shape of the canopy at critical locations may enable controllable and reversible changes to the parachute lift, drag, descent rate, and glide ratio. The materials considered for the smart material based parachutes include: shape-memory polymers, electro-active polymers, shape-memory alloys, piezoelectric based actuators/fibers, fiber optic sensors, and pneumatic based actuators.

Within this work, a state-of-the-art summary of the performance metrics of each smart material technology (wrt. displacement, force, response time, actuation mechanism, reliability, commercial availability, controllability) and how these materials could potentially be utilized in a new parachute design is presented. Each technology is rated for implementation feasibility based on the practical design requirements for parachute systems. The design criteria include smart materials that can produce large strains with high actuation forces. The materials must have low weight, high mechanical flexibility, and high reliability to maintain or improve the operating characteristics of modern parachutes. The response time of the required materials must also be sufficiently short depending on the application (e.g for low-altitude drops). The actuation performance of the smart materials must be controlled. If the actuation performance is not reversible, the parachute must be disposable with minimal costs for materials and manufacturing. The control mechanisms considered for the smart materials include: the application of an electric field, voltage, light, localized temperature change, pneumatic inflation, physical deformation, global temperature change, chemical or pH change, and the application of a magnetic field.

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7643-61, Session 7b

Bio-inspired thorax design for wing flapper of micro-air-vehicle

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Wing-flapping insects are impressive and effective natural flyers. Flight thorax is the oscillating mechanism that flaps the wings. The thorax stores elastic energy and enables efficient flight. This inspires us a bio-mimetic design of wing flapping mechanism for micro air vehicles (MAV). In this paper, we propose a thorax design using compliant flexures and a vibration motor. The thorax structure is excited into resonant vibrations using a vibration motor without gears. This design concept eliminates frictional loss from using gears and revolute joints. Hence, it can potentially reduce the frictional loss of energy, which is an issue for a typical actuator system using a motor and gears.

Two designs of the frames are presented, fabricated and compared. The designs are fabricated using carbon-fiber-reinforced epoxy bonded to a substract of polyimide films. The un-reinforced regions form the flexural joints. A vibration motor with a rotating unbalance mass is adopted to excite the thorax structure. Wing flapping motion is achieved through the lever design mechanism of the thorax and amplifies the vibrating motion into angular displacement of the wing. The prototype of less than 5 grams and thoracic frame diameter of 27 mm was demonstrated to achieve a resonant wingbeat frequency of 20 Hz with wing stroke amplitude of 30 degrees. Its performance is shown to be comparable to those of large insects.

7643-63, Session 7b

Design and demonstration of a fish robot actuated by a SMA-driven actuation system

C. H. Le, H. C. Park, Konkuk Univ. (Korea, Republic of)

Electric motor has been widely used as an actuator in robotic world. However, heavy, large size, noisy, and complicated are some disadvantages of this type of actuator. Recently, artificial muscles have been developed to overcome these problems. As an application of artificial muscles, fish robots have been developed by implementing artificial muscles in their actuation systems. Most recently reported fish robots are driven by shape memory alloy (SMA), ionic polymer metal composite (IPMC), and piezoelectric ceramic (PZT).

This work presents a fish robot actuated by 0.1mm diameter SMA wires. It is aiming to reduce the power consumption as well as the response time. The fish robot has two main parts: the bending actuation system and artificial tail fin. The bending actuation system converts a linear displacement of SMA to bending angle of fish body. The fish robot body is constructed by several bending actuators in order to amplify the bending angle of fish robot. In each segment bending actuator, SMA wires are attached side by side of an elastic beam. The bending motion of the actuator was created due to the contraction and the relaxation of the SMA wires. The elastic energy stored in the elastic beam during heating phase of SMA wire is released in cooling phase, so that the actuator can quickly recover to the initial position. For the artificial tail fin, the SMA wires are embedded to an elastic substrate layer and located between the substrate layer and the skin layer. SMA wires are connected to the substrate layer at several contact points. The skin layers are adhered to the elastic substrate, so that the SMA wires, substrate layer, and skin can bend together during operation. The elastic property of the substrate plays an important role in this application because it provides elastic force which can make the SMA wires to recover faster right after the electric power is switched off.

The SMA wires are heated by using DC power supply. In order to provide a precise control, we experimentally and numerically studied the relationships between strain of the SMA and heating temperature, the bending angle of actuator and input power, and heating current and speed response.

To achieve a large thrust force, body and/or caudal fin (BCF) movement is mimicked. The actuation angle of robotic fish was both estimated by analysis and measured by experiment to verify the design. The tail beat angle and the speed of robotic fish in water are also measured at various input power to test performance of the fish robot.

7643-64, Session 7b

Development of a propulsion system for a biomimetic swimmer and the effect of complex filament on its performance

A. Tran-Le, N. Ha, N. Goo, Konkuk Univ. (Korea, Republic of)

In this paper, a biomimetic propulsion concept inspired by the motility mechanisms of bacteria such as E. Coli was studied basically. E. Coli and other bacteria use rotating one or several helical filaments to swim. The performance of the rotating filament mechanism was estimated by modeling a dynamics of helical wave propulsion. The dynamic model was considered that a rigid helical filament in fluid of viscosity , rotated at one end at frequency with the other free. We applied the Resistance Force Theory (RFT) on this model to calculate the thrust force and required torque rotating the helical filament. The Buckingham PI theorem (non-dimensional analysis) was also used to optimize the design. The non-dimensional analysis results shown that both the thrust force and required torque were functions of geometry only. An optimum design is one yields the maximum thrust force and minimum required torque to rotate the filament. An increase in the amplitude of the helical filament will increase both thrust force and required torque. As for the diameter of the helix, the curve of thrust force looks like parabolic shape and yields the highest thrust force at a value of it. An increase in the wave length of the helix, both the thrust force and required torque dramatically and converge to a certain value. Beside we considered the effect of “complex” filament imitated from Rhizobium Meliloti bacteria on the thrust force. The procedure for making complex filament and plain filament were presented in detail. To validate the theoretical results for helical wave propulsion and compare the complex and plain filament together, an experiment setup was carried out to measure the thrust force produced by single filament in silicone oil. The experimental results were shown to be agreement with the theoretical values predicted by the RFT model and the maximum thrust force of complex filament was achieved at pitch angle s = 450. In addition, we found that the thrust force generated by complex filament had a value about 10 higher than that of plain filament with the same equivalent diameter, de. Moreover, a novel velocity measurement setup was designed to measure the velocity of the robot in more accurate fashion.

7643-107, Session 7b

Biomimetic wing design for the development of pigeon-inspired flapping-wing MAV

N. Mahardika, H. C. Park, Konkuk Univ. (Korea, Republic of)

Pigeon is one of those nature flyers that have very complex wing motion. Their wing motion consists of flapping, lead-lagging, feathering and wing feathers separation. They can also actively flex down their outer wing during upstroke.Many researchers have studied the kinematics of pigeon wing include this feature, but the aerodynamic benefits of that complex motion still not fully investigated. This becomes a challenge for researchers to investigate the effect and benefits of that motion. Many researchers have implemented some structural connections on the wing spar that act as a spring for outer wing flexion, but their flapping mechanism mostly produces only flapping motion without lead-lag motion. We believe that the lead-lag motion also needs to be included in investigating the effect of outer wing flexion. For the investigation of this feature, we have made a flapping mechanism based on slider crank configuration that can create lead-lag motion to mimic the pigeon’s tip path. We have designed and fabricated a 50cm span biomimetic wing based on a pigeon wing, the main spar of the wing is modified by installing the spring between inner and outer wing. Finally, the kinematics test is

conducted to measure the wing amplitude and twisting angles. High-speed camera images of the wing motion are used to evaluate and improve the wing performance. The force measurement by using load cell is conducted to measure the thrust and lift. Based on the analysis of high-speed camera images and force measurement, we can analyze the parameters that affecting the performance of the wing. This study hopefully can contribute to the area of flapping-wing MAV wing design, particularly on the effect of outer wing flexion combined with lead-lag motion.

7643-65, Session 8a

Multiscale analysis of the effect of nanotube functionalization on damping characteristics of polymeric composites

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Chemically functionalized carbon nanotubes have been used as polymer-composite reinforcement in a number of researches [Geng et al, 2002; Zhu et al, 2004; Liu et al, 2004, Gojny et al, 2003, 2005]. Most of the studies are focused on its elastic properties. Very little has investigated the effect of nanotube functionalization on damping properties of polymeric composites, especially with theoretical analysis.

From previous study [Zhou et al., 2004; Liu et al, 2006], the interfacial shear strength between the nanotube and the polymer as well as that between nanotubes in a rope play a very important role in damping characteristics. In this presented paper, the influence of CNT functionalization on interfacial shear strength and hence on damping characteristics of CNT-based composites is investigated with a multiscale model.

The sequential multiscale approach consists of two parts. First of all, the interfacial shear strength between the functionalized nanotube and the polymer is calculated by simulating a CNT pull-out test using the molecular dynamics method. The shear strength values obtained from atomic simulation are then applied to a micromechanical damping model of a representative unit cell of a CNT/polymer composite.

With this multiscale model, polyethylene composites with functionalized SWNTs are investigated. The effect of nanotube functionalization on interfacial shear strength is explored by pulling out the SWNT from crystalline polyethylene matrix which is connected to the SWNT with different number of functional groups. With the shear strength values obtained from molecular dynamics simulation, the effective loss factors of the composites are presented. The analysis results indicate that the nanotube functionalization increases the interfacial shear strength. However, the increased shear strength can either enhance or reduce the effective loss factor of composite, depending on the combined effect of interfacial shear strength and operational stress range.

7643-66, Session 8a

Microfibrous metallic cloth for damping in printed circuit boards

G. T. Flowers, Auburn Univ. (United States)

As a result of the relatively low intrinsic damping in printed circuit boards, vibration and shock loading may excite vibration modes that lead to vibration-induced damage of the PCB and attached components. An investigation of techniques to enhance the damping in printed circuit boards is conducted. Experimental evaluation of the effects of several damping treatments was performed. Of particular interest were the effects of potting materials and microfibrous metallic cloth sandwich configurations. The results from different configurations for each type of treatment are compared and the results discussed. An overall summary of the results is presented and conclusions/ observations are discussed.

7643-67, Session 8a

Broadband pulsed flow using piezoelectric microjets

J. M. Hogue, J. Solomon, F. Alvi, J. Clark, W. S. Oates, Florida State Univ. (United States)

The ability to actively control high speed flows is an area of research that has stemmed from the advances in robust actuators and their integration into aircraft structures including impinging jets, cavities, and jet inlets. These actuators are under development to understand fundamental flow characteristics of a pulsed flow microjet for active flow control. Recent research has shown substantial reductions in flow separation and jet noise using steady mass flow microjets. Reductions in mass flux without performance losses are desired by actively pulsing the microjet. Two piezoelectric actuators have been designed and tested to investigate this concept for broadband flow control. A piezohydraulic actuator was the initial test platform for active flow control. The actuator includes a piezoelectric stack actuator and hydraulic circuit to achieve sufficient displacement amplification to throttle a 400 micron diameter microjet. This system is shown to provide broadband pulsed flow actuation up to 800 Hz. Key parameters contributing to dynamic actuation are shown to include hydraulic fluid behavior, biased microjet air pressure, and voltage inputs to the stack actuator. An actively deforming converging-diverging nozzle was also designed using a compact piezoelectric stack actuator coupled to a micronozzle. The nozzle was designed to achieve an average Mach number of 1.5 and 20%-30% change in Mach number during piezoelectric actuation. The design of the actuator will be given as well as preliminary flow and characterization data. A set of key parameters have been identified and used to guide the design of the actuator. Supersonic flow was achieved as illustrated using micro-schlieren techniques to quantify the flow field during steady and pulsed flow. The new actuator is expected to provide a route towards compact broadband pulsed microjet actuation for a broad class of aerospace flow control surfaces.

TRACK 7: Aircraft, MAV/UAV and Morphing systems

7643-68, Session 8a

Distributed intelligence using gallium nitride based active devices

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This research seeks to develop a novel branch of materials systems called Distributed Intelligent Materials Systems (DIMS) which incorporate actuation, sensing, and electronics as inherent parts of the material structure and have the potential to have intelligence built-in. As a candidate device we highlight a microcantilever optical switch with Gallium nitride (GaN) as host for a DIMS device. GaN is a wide-bandgap compound semiconductor that has several material characteristics, which enable it to outperform other semiconductor materials for electronic applications. In addition, it displays exceptional chemical inertness, has a relatively high piezoelectric coefficient, good mechanical strength and toughness and is transparent to wavelengths in the visible spectrum.

In this research we develop and fabricate a GaN-based, piezoelectrically actuated, microcantilever optical switch/waveguide. While the GaN-material offers the benefits mentioned above, the piezoelectric actuation and the cantilever design provide benefits of lighter weight, compactness, speed of actuation, reduced structural complexity enabling easier fabrication and low wear and tear due to minimal moving parts. The proposed design has a conventional unimorph configuration with GaN actuated in d31 mode. In this configuration, a flat metal electrode and a 2-D electron gas (2DEG) layer are used to apply an electric field in the top layer thereby causing it to extend along the cantilever axis. The passive resistance of the lower layer to this extension causes the cantilever to bend. The

deflection of the unimorph cantilever tip, which is a key variable of interest, depends the cantilever length, applied field, ratio of active/passive layer thicknesses, overall cantilever thickness and the ratio of elastic moduli of active/passive layers.

The unimorph is fabricated as a micro-cantilever by using a GaN on a GaN substrate, with conducting metal and 2DEG electrodes. First, the GaN is deposited using molecular beam epitaxy. The cantilever is then etched using a combination of inductively coupled plasma etching, electron-beam evaporation and liftoff, and a photoelectrochemical (PEC) etch. The microcantilever is subjected to static and dynamic testing to quantify device performance.

7643-69, Session 8a

Nano-silicon based photonic crystal stamps with electron beam lithography (EBL) technology

R. Jannesary, Johannes Kepler Univ. Linz (Austria)

we report on using e-beam lithographically technology for enabling the mass replication of custom-designed and prepared Nano-structures via establishing nanoimprint processes for pattern transfer into UV curable pre-polymes. By EBL, the new nano-fabrication technology based on the concept of disposal master technology (DMT) is suitable for mass volume manufacturing of large area arrays of sub-wavelength photonic elements.

We will present some kinds of PhC and waveguides for fabrication of nanoimprint Electron beam lithography stamps in Si. (a) a photonic crystal of Si-rods in air optimized in that with electron beam lithography (EBL) pattern create on resist and after lift-off, there is a mask of Cr on Si, then the pattern transfer into Si was performed using reacting ion etching with an etch gas. We use the positive resist PMMA for EBL exposure. Resist thickness, exposure dose, development time and parameter for etching have been optimized in this method was fabricated (b) in the second method lift-off was not performed and metal mask was used as master.

7643-70, Session 8b

Variable stiffness fluidic actuator based on F2MC and piezoelectric-hydraulic pump

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Recently, new biological-inspired fluidic flexible matrix composite (F2MC) has been developed for autonomous structural tailoring and high-mechanical-advantage linear/torsion actuator. Although the actuation function and the variable stiffness function of fluidic FMC (F2MC) have been successfully demonstrated, their full potentials are not yet manifested due to the limitations of the currently employed conventional pressure sources and simple on/off valve control action. In order to use F2MC as an actuator, the stand-alone pressure actuation (control) system has to be essentially incorporated. However, current hydraulic/pneumatic actuation systems are bulky and relatively heavy, reducing the promising potential of F2MC actuator (i.e., high power density).

To address the aforementioned issue, we synthesize a new multi-functional fluidic actuator that can provide both high efficient actuation and actively tunable stiffness. This structure design incorporates two innovative ideas: a flexible matrix composite (F2MC) and a compact piezoelectric-hydraulic pump (PHP). By integrating a transverse honeycomb F2MC tube structure with the PHP, one can create a monolithic compliant bending actuator. In addition, one can achieve both the desired shape (position) and variable stiffness through the PHP.

7643-71, Session 8b

Autonomic structural materials with controlled toughening

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The field of Structural Health Monitoring (SHM) has grown significantly over the past few years due to the safety and performance enhancing benefits as well as the potential life saving capabilities offered by the technology. Current advances in SHM systems have lead to a variety of techniques capable of identifying damage; however, few strategies exist for using this information to quickly react to environmental or material conditions needed to repair or protect the system. Rather, current systems simply relay this information to a central processor or human operator, who then decides on a course of action, such as altering the mission or scheduling a repair operation. Biological systems exhibit many advanced sensory and healing traits that can be applied to the design of material systems. For instance, bones are the major structural component in vertebrates; however, unlike modern structural materials, bones have many properties that make it effective for arresting the development and propagation of cracks and subsequent healing of the damaged region. The foremost goal for the development of future adaptive structures is to provide the material itself with the ability to mimic biological systems, such as bones, and autonomously adapt to impede the progression of damage and subsequently heal the damaged structure. One of the challenging issues in the design of autonomous materials is that the materials respond actively in delivering the stimulus to the damage site without complex locating algorithms. In order to overcome this complication, an autonomous material system is devised that uses Shape Memory Polymers (SMPs) with an embedded fiber optic network. Using SMPs, a novel system is developed that employs an optical fiber network as both a damage detection sensor and a network to deliver stimulus to the damage site, initiating adaptation and healing. In the presence of damage, the fiber optic fractures allowing a high power laser diode to deposit a controlled level of thermal energy at the damage site, locally reducing the modulus and blunting the crack tip. The shape memory polymer not only provides a sharp glass transition, but also allows for the application of an induced global pre-strain, which under thermal loads induces the shape memory effect to close the crack. It will be shown that the material can be significantly toughened and that control algorithms combined with the shape memory properties can further increase the toughening effect. The entire system will be able to effectively sense damage and self toughen similarly as bone does autonomously.

7643-72, Session 8b

Non-invasive measurement techniques for measuring bilayers and protein activity in droplet-interface-bilayers

M. A. Creasy, D. J. Leo, Virginia Polytechnic Institute and State Univ. (United States)

Cell membranes are made of phospholipids, proteins, and carbohydrates. The phospholipids are the passive structure of the membrane that acts as a barrier between the inner and outer portions of the cell. The proteins are the active structure of the membrane that allows signaling, energy conversion, and open channels. The carbohydrates are usually attached to either the phospholipids or proteins and assists in the aforementioned activity. A Droplet-Interface-Bilayer (DIB) is an artificial means of making a cell membrane using natural or artificial membrane components. Water droplets in oil are used as an interface for the membrane components to self assemble into an organized structure that mimics a cell membrane. Electrical measurements are used to test the bilayer properties by applying an artificial potential across the membrane and measuring the resulting current. This research shows that the electrical properties of the bilayer can be measured non-invasively (without an electrode placed in the water droplet). The electrodes can touch the exterior of the droplets, where a monolayer is formed, and either attach to the monolayer or

form a bilayer at the droplet electrode interface. The actual connection is dependent on electrode preparation and both scenarios will add a resistor and capacitor (RC) circuit to the electrical measurement of the system. A model of the RC circuit is incorporated into the system model and properties of the DIB are extracted from the system model that is matched to the measured data.

7643-73, Session 8b

Constructing precise bio-inspired material systems in flexible substrates using the regulated attachment method

S. A. Sarles, D. J. Leo, Virginia Polytechnic Institute and State Univ. (United States)

The principles of molecular self-assembly permit the construction of synthetic biomolecular material systems that mimic the architecture and active functionality of their natural analogues. One such material system is the lipid bilayer, a two-molecule thick fluid membrane composed of phospholipid molecules that mimics the plasma membrane of plant and animal cells. Researchers have formed lipid bilayers using a number of techniques since the early 1960's and their findings provided valuable information about the structural properties of cell membranes and the functions of transmembrane molecules, such as proteins. However, the fragility of these molecular assemblies has prevented their use beyond controlled studies in a laboratory environment. The droplet interface bilayer (DIB) that emerged in recent years provided an alternative approach for bilayer formation, in which a lipid bilayer is formed at the interface of lipid-encased water droplets submersed in oil, and showcased the utility of active biomolecular systems. The primary advantage of this technique is the ability to construct precise biomolecular material systems, where the arrangement and composition of the droplets determines the collective properties of the network. Early demonstrations include a light-activated current source using bacteriorhodopsin proteins and a full-wave bridge rectifier with genetically-modified alpha-hemolysin channels.

However, the advantages of DIB networks are offset by several challenges in creating large arrays, including: dispensing and manipulating large numbers of small droplets (<100μm diameter), altering the compositions of molecules in specific parts of the network, controlling the sizes of the interfaces, and designing the system for portability. Recently, we developed a new method for bilayer formation, called the regulated attachment method (RAM), in which durable lipid bilayers are formed in a flexible substrate. This technique employs control of a deformable substrate through an applied mechanical force to regulate the attachment of adjacent lipid-encased aqueous volumes submersed in oil. RAM further departs from the DIB in that the size of a lipid bilayer is controlled by varying the dimensions of an aperture in the flexible substrate that separates neighboring aqueous volumes. In this manner, the regulated attachment method provides key advantages over droplet interface bilayers for constructing durable and useful biomolecular networks. First, the size of the bilayer can be prescribed and, unlike DIBs, bilayer size is independent of the size or shape of either aqueous volume. Second, RAM affords precise control over the composition of the network, even allowing the introduction of species into specific lipid bilayers after network formation. Third, the regulated attachment method enables direct integration into portable microfluidic lab-on-chip type devices for creating precise biomolecular networks that feature durable lipid bilayers assembled on the micro- or sub-micron scale.

Our work from here is focused on developing more-complex flexible substrates that employ the regulated attachment method to create self-contained biomolecular networks featuring tailored lipid bilayer interfaces. Specifically, we plan to investigate alternative methods such as embedded magnets for opening and closing apertures and develop novel applications for these networks, including color-change materials and low-power energy-harvesting networks.

7643-74, Session 8b

Comparison of the throughput of techniques for prototyping protein-bound suspended bilayer lipid membranes

V. B. Sundaresan, Virginia Commonwealth Univ. (United States)

Suspended lipid bilayer membranes (BLM) offer an ideal environment for characterizing membrane-bound proteins used in biosensors, energy harvesting devices and drug screening platforms. The plethora of techniques used for forming suspended BLM relies on manual processes to trigger self-assembly and protein reconstitution. The most popular techniques such as painting, tip-dip method, Langmuir-Schaeffer technique, microfluidic platforms, droplet interface techniques and agar-supported membrane self-assembly while being successfully used to demonstrate protein reconstitution have not been compared against each other for their throughput of membrane formation. The substrate material, protein reconstituted into the membrane and the orientation of the membrane limits the applicability of each technique. A one-on-one comparison of the membranes formed by different techniques is missing and hence this article attempts to address the void by comparing the throughput of membrane formation, long-term stability of the membrane and applicability of different techniques for different protein-based devices. An automated fabrication setup for each technique (painting, falling droplet, microfluidic platform and tip-dip method) is developed so that the membranes formed from a large sample (>50) is compared with each other. The reconstitution of a suitable protein such as alamethicin, gramicidin and GPCR cell lines will be tested for protein activity to estimate the efficiency of reconstitution. The results will be significant to compare and contrast the membrane self-assembly processes and protein reconstitution by different techniques and to extend each of these techniques to form a block co-polymerized BLM for protein-based devices.

7643-75, Session 9a

Post-buckled precompressed (PBP) solid state adaptive rotor

R. M. Barrett, R. Barnhart, L. Kerth, The Univ. of Kansas (United States)

The paper begins with a brief historical review of solid state adaptive rotor systems which stretch back to patents first filed in 1989. An historical summary takes the reader through early linear/conventional rotor systems of the 1990's and the lull in progress experienced in the late 1990's prior to the discovery of nonlinear/postbuckled actuation methods. This paper covers modeling techniques and design principles for Post-Buckled Precompressed (PBP) Solid State Adaptive Rotors using piezoelectric torque-plate actuators mounted at the rotor hub. The nonlinear solid state arrangement allows for full control of blade pitch deflections through +26/-7 deg, flapping through +18/-5 deg. and even lead-lag articulation of +/-5 deg. In addition to allowing conventional blade motions and control with a solid state mechanism, pitch-flap equivalent $\delta 3$ coupling is achieved by using inherent properties of the actuation system. Analytical modeling begins with fundamental Classical Laminate Plate Theory expressions. These are expanded to include plate imperfection models to account for Post-Buckled Precompression. A 20cm x 5cm PZT-5H piezoelectric torque-plate actuator was built into the root of a helicopter rotor blade assembly. The 120cm diameter rotor assembly was whirl-stand tested through 700 RPM showing excellent correlation between theory and experiment. High speed tests were conducted at rates of up to 5/rev., again, showing excellent correlation between theory and experiment. The paper concludes with a feasibility assessment, showing the PBP rotor possesses three times more control authority than the next closest adaptive control technique for collective, cyclic and high speed, high authority individual blade control.

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7643-76, Session 9a

Robustness of orthogonal eigenstructure control to actuators failure

M. Rastgaar Aagaah, Massachusetts Institute of Technology (United States); M. Ahmadian, Virginia Polytechnic Institute and State Univ. (United States)

Orthogonal eigenstructure control has been recently developed by the authors for vibration control in structures. This control method is applicable to the multi-input multi-output linear systems. In this paper, the robustness of the method to the failure of the actuators is investigated. It is shown when an actuator fails, the control gain matrix still is able to control the systems, since the closed-loop eigenvectors are within the achievable eigenvectors set. A system of lumped masses has been used to elaborate the method; then, the problem of failed actuators in the vibration control of a plate is investigated. Finite element method is used for modeling the plate to simulate the dynamical behavior of the system. Five cases are considered and the suppression of the vibration in a plate with three working actuators is compared to the suppressed vibration of the plates with one failed actuator. Also, the behaviors of the system with failed actuators are compared to the systems that are designed to operate with exactly lesser control actuators. It is shown that the number of moved closed-loop eigenvalue pairs is equal to the number of working actuators. The closed-loop poles in all the systems are moved to the vicinity of one specific area, which results in a robust control.

7643-77, Session 9a

Shim stack deflection analysis in hydraulic dampers using energy methods

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This paper presents a detailed analysis of the deflection of the shim stacks used in hydraulic dampers. In hydraulic dampers, a stack of circular disks (shims) is mounted on each side of the main piston to create a pressure drop as the hydraulic oil is passed through the piston from one side to the other. A stiff shim stack creates a high pressure drop across the piston, resulting in high damping. A softer shim stack creates less pressure drop and smaller damping. In practice, shims can be added or removed from the shim stack assembly to tune the damper and generate the desired damping force characteristics as a function of velocity. Tuning a damper requires taking the damper apart, making the changes to the shim stack assembly, and putting the damper back together. This takes a considerable amount of time and effort. Therefore, mathematical modeling of the shim stack assembly becomes a crucial part of the analysis of hydraulic dampers.

The goal of the study presented here is to provide a model of the shim stack assembly in order to accurately predict the level of damping for different configurations of the shim stack. The shims that are stacked on each other will deflect under the pressure created by the hydraulic oil, and at the same time slide against each other. This important characteristic of the shim stack needs to be accounted for in the mathematical model and makes the analysis complicated. For the sake of simplicity, in past studies the shim stack is approximated by the deflection of a single disk and formulas for a single disk are used. This, however, introduces a significant amount of error in the damper hydraulic model. In this paper, the deflection of shim stacks is analyzed and compared with the single disk approximation. It is found that this approximation fails to agree with the more accurate model of representing the shims individually. Therefore, a more detailed and accurate model is necessary for better simulating the damping characteristics of hydraulic dampers as a function of relative velocity across the damper.

This study provides the results of an analytical study that considers different cases. First, the shear deformations are neglected. Then the shear deformations are included in the model and the results are compared with the simple case. It is found that the shear deformations are not negligible and should be included in the mathematical model. Energy and variational methods are used to derive the governing equations and the resulted governing equations are solved using the Rayleigh-Ritz method in conjunction with the Lagrange multipliers method. Furthermore, the mathematical model of the shim stack is implemented in a mono-tube hydraulic damper model and the effects of various shim stack configurations are studied.

7643-78, Session 9a

Free space optical coupling of embedded reflection-based fiber Bragg grating sensors through panel surfaces

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In recent decades, optical fiber has proven useful for many sensor applications. Specifically, fiber Bragg grating (FBG) sensors have shown great utility for integrity management and environmental sensing of composite structures. One major drawback of FBG sensors however, is that they suffer from cumbersome and fragile techniques for bringing the sensing light into and out of the structure since the optical fiber must be routed through the surface of the composite (i.e. pigtailing). In this paper, a novel method of free space passive coupling of light has been investigated. The use of 45-degree-angled mirrors integrated into fibers was used as an input and output coupling technique. With the difficulty of directly integrating the mirrors onto the tiny single mode fibers, a novel method of coupling to the sensor via splicing and fusing a multimode fiber to the single mode FBG was explored. Using this method, we have previously demonstrated free space optical coupling to transmission-based FBG sensors embedded inside a composite panel. In this paper, we are able to couple the reflected light of the embedded FBG sensors through the panel surfaces with the 45-degree-angled mirrors. Therefore, we conclude that this novel space coupling method can be used to effectively couple the transmitted and reflected light for embedded FBG sensors.

7643-79, Session 9a

Vibration based analysis of an increasing delamination in a carbon/epoxy composite structure

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This paper reports on the assessment of variable damage configurations in a carbon/epoxy composite material using its vibration response. This paper highlights the application of vibration based testing on Carbon/Epoxy composite beams for damage detection. Such composites are commonly used in the aerospace and marine industry. The study comprises of testing carbon/epoxy composite beams with various embedded delaminations with a mechanical actuator and a Scanning Laser Vibrometer (SLV) as a sensor for recording the frequency response and the subsequent analyses of the acquired dynamic response based on Displacement and Curvature Mode Shapes. This paper also reports on an innovative way of extending an existing delamination by a fatigue crack-growth technique. Pre- and Post-crack growth curvature-mode shape analyses were undertaken, reported and compared. . The ASTM E399-90 standard is used for the experiment and a careful fatigue crack growth routine was designed and implemented to advance the delamination in a controlled manner.

Composite materials are supplanting conventional metals in aerospace, civil and marine industries. Composite materials have excellent mechanical properties such as good strength-to-weight ratios, however they are prone to sub-surface flaws such as delaminations, which are difficult to detect. Thus, it is important that the initial defect be detected before it initiates into a serious flaw. There are a number of local- and global-damage detection methods for the detection and localisation of the damage in a composite material.The research study conducted

here primarily deals with the structural health monitoring of composite materials by analyzing vibration signatures acquired from a laser vibrometer. The primary aim of the project is to develop a vibration based structural health monitoring (SHM) method for detecting flaws such as delamination within the composite beams. Secondly, the project emphasizes on the method's ability to recognize the location and severity of the damage within the structure. The system proposed relies on the examination of the displacement mode shapes acquired from the composite beams using the laser vibrometer and later processing them to curvature mode shapes for damage identification and characterization. Other identification techniques such as a C-scan has been applied to validate the location and size of the defects with the structures tested.

In addition to this, this paper also introduces a method to experimentally compute the critical stress intensity factor, KIC based on ASTM E399-90 for the composite beam. Based on this, a technique for extending the defect has been proposed and validated using concepts of fatigue and fracture mechanics. The experimental procedure to extend the defect using fatigue was validated using the SLV system. Displacement and Curvature mode shapes were acquired and analyzed post-fatigue crack extension.

Upon analyzing and comparing the displacement and curvature mode shapes before and after crack extension, the original and extended delamination were identified satisfactorily.The output from these plots enabled the successful identification of both the location and extent of damage within the structure with an accuracy of 96.5%.

This paper demonstrates the feasibility of examining features of curvature mode shape analyses when comparing its effect on different damage configurations. In the discussions above, it is clear that damage parameters such defect size can be delineated using the curvature mode shape analyses. The fatigue crack growth technique employed in this paper enabled an escalation in the damage size without necessarily introducing additional damage features such as impact and local indentations around the original damage configuration. This technique thus, enables an added dimension of study of damage analyses, which has proved perhaps too cumbersome and complex in the past. The experimental program here comprises of testing Carbon/epoxy composite laminated plates with embedded delaminations both before and after crack propagation using the SLV actuator-sensor measurement system. This was corroborated using Finite Element Analyses (FEA) models.

7643-80, Session 9a

Modeling and control for a planar robot with one rigid link and one flexible link

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This work describes the modeling and control of

an experimental platform associated to a two joint robot with one rigid link attached to a main frame which is fixed to the base of the robot and one flexible link attached to the end of first rigid link to form a robotic arm, whose motion is restricted to an horizontal plane, so that the gravity effects are neglected. The modeling problem is addressed using the Euler-Lagrange formalism and the so-called Euler-Bernoulli beam equation is used to describe the dynamical behavior for the flexible link. Since the flexible link is attached to a moving frame associated to the rigid link motion, the clamped-free modal shapes cannot longer be assumed in the modeling of the flexible link. Thus, the modal shapes are derived by using inertial boundary conditions at both extremes of the flexible link and its first three modal shapes are included in the model in order to achieve good accuracy. The design, construction and integration of an experimental set-up developed for this work is also presented. The vibration amplitude of each modal shape considered in the flexible link is estimated via a set of three strain gages fixed at specific locations along the flexible link. These strain gages are employed as deflection sensors for the flexible link. Two main control schemes are then devised for controlling the end tip position of the flexible robot. The first one is the so-called passive velocity feedback based on the backstepping technique used for passivity-based control designs of nonlinear systems performing a cascade, because the flexible robot presented in this work can be described as a cascade interconection of two dynamical systems being the set of rigid modes the first system and the set of flexible modes the second system. The second one is the energy-based control method called strain feedback. Stability analyses are provided for both control methods. Finally, the overall system performance is illustrated by some experimental results obtained with both control methods.

7643-81, Session 9b

Configuration of a shear web based actuation system

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Shape adaptive systems and structural configurations are necessary to fulfil the demands of a future unmanned aerial vehicle structure. Predominantly the present approaches are based on a passive load-bearing structure having smart actuation systems deforming the passive structural configuration elastically in the wanted shape. Therefore the actuation system can be based on discrete actuators, like electrically driven motors using gearing systems to transform the displacement into the structure or on smart material configurations places on the load bearing passive structure, deforming the structure within the elastic region into the wanted shape.

Using smart materials within load-bearing structures, elastic and static strength properties vary between passive and active structures. Matching these properties is a great challenge for future structural configurations. This is a successful approach for certain applications, e.g. smart rotor blade.

The availability of two-dimensional smart actuator configurations with distinct actuation orientation allows the definition of a distinct load bearing active structure. Therefore the so called "web" of a spar-equivalent configuration was substituted by such a smart material actuator also known as macro fibre composite (MFC). Activating the web of the active cantilevered spar-configuration is resulting in a free end displacement. The main advantage lies in the fact that this approach will allow larger active displacements in comparison to a passive structural configuration with applied smart material actuators.

Within the paper the process of developing the shear web based actuation system with configuration details will be illustrated and future steps will be proposed.

7643-82, Session 9b

Piezoelectrically actuated insect scale flapping wing

S. Mukherjee, R. Ganguli, Indian Institute of Science (India)

Research interest on micro air vehicles (MAVs) has been growing because they have a large number of potential military and commercial applications. The potential applications of current fixed wing MAVs are limited due to maneuver constraints, incapability to hover and stall at low speeds. Rotary wing MAVs can hover but they suffer from low figure of merit, high power consumption and significant noise signatures. Nature provides flapping flyers such as birds and insects which represent a very successful design for intelligent MAVs with much better performance than conventional wings and rotors in terms of hovering capability, maneuverability, acoustic signature, specific power requirement etc. Lightweight, flexible and adaptive/morphing wing structures make an important contribution to the overall performance of a flapping wing MAV. Thus, MAV flapping wing design represents one of the major challenges to efficient flight in the low Reynolds-number regime. Currently, flapping wing mechanisms rely on pneumatic and motor-driven flapping actuators which lead to high weight and system-complexity. Moreover, natural flapping flyers generate lift and thrust using complex wingbeat kinematics which can not be easily mimicked with these conventional actuators. Piezoelectric fan (piezofan) which couples a piezoelectric unimorph to an attached flexible wing is competent to produce large deflection especially

at resonance. In this paper, we analyze and design an insect-scale piezoelectrically actuated flapping wing. Numerical simulations are used to achieve several aspects of insect wingbeat kinematics by the flapping wing. Finally, aerodynamic performances are evaluated using a design oriented model for the unsteady aerodynamics of a flapping wing.(TRACK 2: Biological-inspired Systems and Bio-MEMS)

7643-84, Session 9b

Modeling and experimental validation of a bistable mechanism for chord extension morphing rotors

T. E. Johnson, M. I. Frecker, F. Gandhi, The Pennsylvania State Univ. (United States)

A concept for SETE plate extension that was recently proposed is the use of a bistable arch for chord extension. In the previous work, the bistable concept is applied to a helicopter rotor blade. In this work, the developed concept for SETE plate extension is modeled and experimentally validated. There are four foci of this paper: (1) Stress Analysis of the Arch, (2) Model Validation via Experiment, (3) Force Study using Nonlinear Finite Element Analysis, and (4) Actuation using SMA Wires. A stress analysis is conducted on the arch because the living hinges possess high levels of Von Mises stress which could lead to yielding and facture. Following the stress analysis, the arch with living hinges is fabricated using Delrin and tested using a 10kN Instron machine. An experiment is conducted using the Instron machine where force versus displacement data is measured for the arch and compared to the Non-Linear FEA model. Following validation of the numerical model, additional force studies are conducted using the Non-Linear FEA model to determine arch robustness while subjected to aerodynamic load. Lastly, SMA wires are added to the arch to actuate the arch between its stable states. The modeling and experimental validation of the arch-plate system are expected to show that the bistable arch and plate system is an effective solution to aircraft chord extension.

7643-85, Session 9b

Aircraft dynamics and wind tunnel testing of two linked UAV systems

E. A. Cuji, E. Garcia, Cornell Univ. (United States)

This paper presents an analysis of close proximity aerodynamics and aircraft dynamics of two conjoined UAVs. Conjoined UAV concept allows for rapidly deployable ISR platform using individual UAVs with wingspans small enough to be deployed from any general aviation airfields. Then individual UAVs will link at high altitude to create an aerodynamically efficient aircraft which has long endurance capabilities and can be able to cruise for extended periods at very low power. As the UAV approach each other for wingtip docking there will be strong aerodynamic coupling between the UAV wings tips. Determining the aerodynamic coupling effects on all the forces and moments is essential to determine a trajectory and controls for each UAV to perform the docking maneuver. Simulation and wind tunnel testing of close proximity effects on lift, drag, roll pitch and yaw moments for two UAV wings will be performed. The proximity aerodynamics effects between the UAVs wings will be analyzed as a function of its relative position in all three directions: chord-wise (x - direction), span-wise (y - direction), and vertical direction (z - direction).

A look-up library of aerodynamic forces and moments for all relative positions and angles of attack between the two UAVs will be developed. In this study we will examine how the close proximity aerodynamics affects the dynamics and stability of the UAVs. The aircraft dynamics analysis will be done in Simulink, which will include the close proximity aerodynamic look-up library. An aerodynamic disturbance intensity field will be performed, utilizing both simulation and wind tunnel data, to determine a trajectory for the two UAVs to approach each other for docking. A wind tunnel verification of the close proximity aerodynamic and dynamics test will be performed.

I want to submit this paper to the following track:

TRACK 7: Aircraft, MAV/UAV and Morphing systems

7643-86, Session 9b

Ornithopter transition trajectories

J. M. Dietl, E. Garcia, Cornell Univ. (United States)

Current ornithopter research concerns ornithopter construction, power sources, wing design, maximizing thrust, energy efficiency, steady flight trajectories, and flight stability. Another goal is to control unsteady maneuvers: the transition from hovering flight to forward flight, turns, and vertical takeoff and landing.

The design of stable trim conditions for forward flight and for hover has been achieved. In forward flight, an ornithopter is configured like a conventional airplane or large bird. Its fuselage is essentially horizontal and the wings heave in a vertical plane. In hover, however, the body pitches vertically so that the wing stroke in the horizontal plane. Thrust directed downward, the vehicle remains aloft while the downdraft envelops the tail to provide enough flow for vehicle control and stabilization. To connect these trajectories dynamically is the goal.

The naïve approach-to choose two stable trajectories and switch between them-has been accomplished. A new approach is to establish an open-loop trajectory through a trajectory optimization algorithm-optimized for shortest altitude drop, shortest stopping distance, or lowest energy consumption. This path itself could be stabilized.

This serves to establish the feasibility of new maneuvers in mechanical flapping flight. It also will make it easier to perform the maneuvers by computer assisted control or by providing an example for a pilot to use.

7643-87, Session 10a

Adaptive control of base-isolated buildings using piezoelectric friction dampers against near-field earthquake

O. E. Ozbulut, M. Bitaraf, S. Hurlebaus, Texas A&M Univ. (United States)

This paper investigates the effectiveness of two adaptive control strategies for modulating control force of piezoelectric friction dampers (PFD) that are employed as semi-active devices in combination with laminated rubber bearings for seismic protection of buildings. The first controller developed in this study is a direct adaptive fuzzy logic controller. It consists of a higher-level supervisory fuzzy controller and a sub-level direct fuzzy controller. In the hierarchical control scheme, high-level controller modifies universe of discourse of both premise and consequent variables of the sub-level controller using scaling factors in order to determine command voltage of the damper according to current level of ground motion. The sub-level fuzzy controller employs isolation displacement and velocity as its premise variables and command voltage as its consequent variable. In order to specify appropriate scaling factors for variables of the sub-level controller, the high-level controller uses ground velocity as its input variable to acquire information on the characteristics of seismic excitation.

The second controller is based on the simple adaptive control (SAC) method, which is a type of direct adaptive control approach. The objective of the SAC method is to make the plant, the controlled system, track the behavior of the model or the structure with the optimum performance. By using SAC strategy, any change in the characteristics of the structure or uncertainties in the modeling of the structure and in the external excitation would be considered because it continuously monitors its own performance to modify its parameters. Here, SAC methodology is employed to obtain the required force which results in the optimum performance of the structure. Then, the command voltage of the PFD is determined to generate the desired force.

For comparison purposes, an optimal controller is also developed

and considered in the simulations together with maximum passive operation of the friction damper. Time-history analyses of a base-isolated five-story building are performed to evaluate the performance of the controllers. Fault-normal and fault-parallel components of eight historical earthquakes are used as external excitation. A total of nine performance indices are defined and computed for each controller to assess the simulation results. Results reveal that developed adaptive controlllers can succesfully improves sesimic response of the base-isolated buildings against various types of earthquakes.

TRACK 3

7643-88, Session 10a

Vibration absorption in a building like structure by means of piezoelectric patches and positive acceleration feedback

M. A. Rios, G. Silva-Navarro, Ctr. de Investigación y de Estudios Avanzados (Mexico)

This paper is about vibration absorption in a building like structure, by means of piezoelectric patches. The experimental plant consists in a bolted aluminum structure. It is approximately 3 ft high and has three levels. Piezoelectric patches are used to actuate the structure. A piezoelectric accelerometer is used to sense the vibration in the structure. The whole structure system is on a frictionless slider. An electrodynamical shaker is used to perturbate the structure at several harmonic conditions. Modeling of the structure is made by finite elements. To proper identify structural parameters in the experimental plant, modal analysis techniques are used. The experimental plant is instrumented and connected to a personal computer via a data acquisition (DAQ) system. The DAQ software is a National Instruments CompactDAQ system. Reading the sensors and closed loop control are implemented using LabVIEW software. The control scheme is a Positive Acceleration Feedback. It gave god performance in a wide range of frequencies. Numerical and experimental results are shown.

7643-89, Session 10a

Using coupled piezoelectric circuits to enhance damage detection of periodic structures

J. Zhao, J. Tang, Univ. of Connecticut (United States)

Spatially periodic structures such as turbine bladed-disk are widely used in engineering systems. The timely detection of damage/fault in these structures has obvious significance. Modern sensing technologies, such as the blade-tip-timing technology, allow the measurement of vibratory response of rotating bladed-disks, which yields the possibility of on-line health monitoring. Generally, the damage-induced frequency change is small. Moreover, the natural frequencies for such structures generally are clustered, which makes it difficult to use the frequency-shift information to analyze damage occurrence. In this research, we propose to integrate identical and coupled piezoelectric circuitries to all substructures, aiming at amplifying the vibration pattern difference induced by the damage occurrence. Specifically, circuitry elements leading to negative resistance will be incorporated. It will be shown that properly designed negative resistance elements and coupling capacitances can greatly amplify the damage-induced response difference, thereby highlighting the damage occurrence in the inspection stage. We carry out systematic analysis to demonstrate that such amplification effect is robust with respect to the inherent mistuning of the healthy structure.

7643-90, Session 10a

Integration of encapsulated piezoelectric actuators in highly loaded CFRP structures

F. Bachmann, P. Ermanni, ETH Zürich (Switzerland)

This work has been inspired by scientific and technological challenges investigated in the frame of the European research project DREAM. This strongly interdisciplinary project aims at the development of novel approaches for structural vibration damping with piezoelectric actuators and autonomous shunt circuits.

During the last decades, vibration damping using piezoelectric actuators has been intensively investigated. Fundamental research in the area of actuators ultimately led to the realization and commercialization of ready to use actuators with well defined interfaces for electrical contacting. However, actuators available on the market are well-suited for superficial applications. Thus structural integration of piezoelectric actuators into composite structures still remains an actual field of research. Open issues concern the development of viable solutions for the integration of piezoelectric actuators and shunt circuits into an electrically conducting environment such as a CFRP laminate.

Besides, wiring and connection to the shunt circuit, mechanical integrity of the host structure, strength and damage tolerance of the smart damping system are of paramount importance. These challenges become even more evident, when dealing with high loading conditions, exceeding the allowable strain of commercially available actuators. In this context our contribution is presenting a novel integration method based on a mechanical pre-stressing of the monolithic piezoelectric actuator. Numerical and experimental investigations conducted in our lab show that this solution clearly has a beneficial impact on the failure onset of the piezo-ceramic element.

7643-91, Session 10a

An active non-contact radial and axial bearing system actuated by high power piezoelectric transducers

S. Zhao, J. Wallaschek, Leibniz Univ. Hannover (Germany)

A novel active squeeze film journal bearing actuated by high power piezoelectric transducers is developed aiming for noncontact axial and radial suspension of a rotating. The bearing system includes a journal bearing and a thrust bearing, both based on squeeze film ultrasonic levitation. The journal bearing consists of three piezoelectric transducers mounted on housing. Each transducer has a concave radiation surface which covers 100 degrees of a cylindrical surface. The thrust bearing consists of a circular plate driven in its flexural vibration mode by a piezoelectric transducer. An electromagnet motor is built into the spindle to rotate the spindle at high speed.

Mathematical models based on Reynolds equation are developed to predict the levitation force of the proposed bearing system. Both analytical and numerical solutions are carried out. The analytical results give good insight to the characteristics of the system with acceptable accuracy. The numerical results agree well quantitatively with the experimental results. The analytical model is integrated into the model of the electro-mechanical system to describe the total dynamics of the bearing system. Experimental results are carried out using a prototype system. The spindle is suspended in both axial and radial directions without mechanical contact. The run-out errors at various rotational speeds are measured. The maximum radial and thrust load-carrying forces are measured as 53 and 120 N. The axial and radial position of the spindle is measured by the integrated eddy current sensors. Positioning of the spindle is realized by actively adjusting the vibration amplitudes of the transducers.

(Track 5)

7643-92, Session 10a

Semi-solid state adaptive impedance composites for HIRF protection

R. B. Bramlette, M. T. Brennison, R. M. Barrett, The Univ. of Kansas (United States)

This paper investigates the feasibility of piezoelectric-based adaptive-impedance composites (AIC) as a method of protecting aircraft equipment from lightning strike events and the resultant high-intensity radiated fields (HIRF). The paper begins with a summary of a typical aircraft lightning strike event and the requirements necessary to shield hardware from the effects. The paper then describes the development of the AIC, and the mechanics involved in the impedance-based switching effect. To further explain and analytically derive the performance of the AIC, classical laminated plate theory (CLPT) and plate vibration theory were applied.

The paper then describes the manufacture and high voltage testing of several AIC prototypes built to a weight of 15 g (0.53 oz.) and a material cost under $20. Testing revealed that the AIC architecture provided closed- to open-circuit switching as fast as 77 µs. The voltage necessary to alter the AIC's impedance was observed between 20 and 60 V DC. Slightly altering the dimensions of the AIC appeared to control this 'activation voltage.'

The paper closes with an evaluation of the AIC architecture comparing the test data and the analytical predictions with the lightning strike data gathered by ONERA which indicated the AIC speed was over 30 times faster than the necessary minimum to shield equipment from HIRF. This final evaluation also includes a comparison of the AIC's performance and architecture to conventional MOSFET-based switching in similar high voltage applications.

7643-93, Session 10a

Multi-cell active acoustic metamaterial with programmable bulk's modulus

A. M. Baz, Univ. of Maryland, College Park (United States); W. N. Akl, Nile Univ. (Egypt)

Considerable interest has been devoted to the development of various classes of acoustic metamaterials that can control the propagation of acoustical wave energy through these materials. However, all the currently exerted efforts are focused on studying passive metamaterials with fixed material properties. In this paper, the emphasis is placed on the development of a new class of composite one-dimensional acoustic metamaterials with effective Bulk's modulii that are programmed to vary according to any prescribed pattern along the volume of the metamaterial. Actively controlled Helmholtz resonators coupled with the main acoustic cavities are introduced to provide the capability for programmable effective Bulk's modulus. The theoretical analysis of this class of multi-layered composite active acoustic metamaterials (CAAMM) is presented and the theoretical predictions are determined for an array of fluid cavities coupled with an array of controllable Helmholtz resonators with piezoelectric boundaries. These smart boundaries are used control the overall Bulk's modulus of the individual cavity through direct acoustic pressure feedback. The interaction between the neighboring cells of the composite metamaterial is modeled using a lumped-parameter approach. Numerical examples are presented to demonstrate the performance characteristics of the proposed CAAMM and its potential for generating prescribed spatial and spectral patterns of Bulk's modulus variation. {Work funded by ONR]

7643-94, Session 10a

Effects of piezoelectric nonlinearity on helicopter vibration reduction

O. Ozdemir Ozgumus, Istanbul Teknik Üniv. (Turkey); D. H. Hodges, Georgia Institute of Technology (United States)

The purpose of this paper is to present the development of an asymptotically correct electro-mechanical composite beam model that accounts for the nonlinear behavior of piezoelectric materials and to evaluate the effects of this nonlinear formulation on the vibration reduction problem of composite helicopter blades that have actively controlled plain trailing edge flaps. Most studies related to active control of helicopter vibration using smart materials neglect the presence of nonlinearities. To the best of the authors' knowledge, this is the first time that the effects of nonlinear constitutive equations of piezoelectric materials on helicopter vibration reduction are inspected.

In order to introduce the piezoelectric nonlinearity into the formulation, an extended expression of the strain energy per unit length is considered as a starting point. Strain and electrical field components have been derived and substituted into the strain energy per unit length. After this step, the variational-asymptotic method is to be applied to obtain an asymptotically exact strain energy formulation for the electro-mechanical composite beam model. Two-dimensional cross sectional analyses is to be carried out to obtain the cross sectional stiffness constants. The geometrically exact beam theory, which takes into account all possible deformations of the beam and which has the small strain assumption as the only restriction, is going to be used to derive the one-dimensional exact beam equations. The cross sectional constants, which will have been derived as a result of the cross sectional analyses, are going to be used in these one-dimensional exact beam equations. The composite blade model, the actively controlled trailing edge flaps and the actuators are going to be modeled in the multibody dynamics code DYMORE, which uses the geometrically exact beam theory.

7643-95, Session 10a

Fabrication of a piezofiber/aluminum composite and its characterization

H. Asanuma, T. Chiba, J. Kunikata, Chiba Univ. (Japan); H. Sato, National Institute of Advanced Industrial Science and Technology (Japan); M. N. Ghasemi Nejhad, Univ. of Hawai'i (United States)

This paper presents fabrication and characterization of a metal-core lead zirconate titanate (PZT) fiber/aluminum composite. In order to embed the fragile fiber in the matrix, the interphase forming/bonding (IF/B) method invented by Asanuma, which has already enabled embedding fragile optical fiber with a FBG sensor in an aluminum matrix, was applied. The effects of fabrication conditions, that is, hot-pressing condition such as temperature, pressure and time, and the size of the U-groove to align and protect the fiber, on the microstructure of the composite were investigated. The optimum conditions obtained to embed it without fracture and chemical reaction were the temperature of 873 K, the pressure of 2.2 MPa and the period of 2.4 ks in a vacuum of 100 Pa at the U-groove diameter and depth of approximately 0.3 mm. By measuring the output voltage generated from the composite in the sizes of 20 mm x 20 mm x 0.55 mm having a piece of the fiber of 20 mm long and 0.2 mm in diameter with a platinum core of 0.05mm in diameter in the center of the matrix, which was poled at 300 V for 1.8 ks after the hot-pressing and attached on a plate and vibrated, it was clarified that it generates notably high voltage such as 86.6.7 mV at a very small strain of 0.00142 % at the oscillation frequency of 19.7 Hz and its waveform corresponds well with that of the strain measured with a strain gauge attached on it.

7643-145, Session 10a

Design, fabrication, and experimental results of a peristaltic micropump using LIPCAs with flexibly supported diaphragms

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The micropump is one of the important components in micro-fluidic systems such as micrototal analysis systems, lab-on-a-chips, and micro-dosage systems. Many kinds of actuators are used to make the diaphragm of micropump: piezoelectric, thermopneumatic, electrostatic and electromagnetic actuators are widely studied. Among these kinds of actuators, the piezoelectric actuator was the first to be used in micropump. This paper presents the design, fabrication and experimental results of a peristaltic micropump using lightweight piezo-composites curved actuators (LIPCAs) as its diaphragms with flexible supporters. The most important parts of the micropump, the diaphragms, are made of LIPCAs due to their advantages of short

response time, high output force and high displacement at high operational frequency. The high vertical deflection of circular LIPCAs enhances the flow-rate of the micropump and reduces the death volume of pumping chamber to make the micropump self-priming. In addition, thin PDMS layers playing the role of active valves are located on the top of diaphragms in the inlet and outlet pumping chambers to prevent the reserved flow and maintain high back-pressure. Moreover, a flexible supporting method is introduced to improve the performance of the actuators. The flexible supporters for the diaphragms are made of PDMS material for its low level of stiffness and good sealing property. Experiments are conducted to investigate the performance of the micropump and also check the leakage of active valves during closing condition. With LIPCAs and a flexible supporting method, the performance of the micropump is improved. This peristaltic micropump is found to be a promising candidate for bio-medical application due to its bio- compatibility, portability, bi-directionality, and simple effective design.

7643-96, Session 10b

The innovative direct driving volume control based AMD system for structural vibration control

C. Zhang, Harbin Institute of Technology (China)

The research and application of vibration control techniques for civil engineering structures have made a significant progress during the last several decades. Some new devices have been successfully applied in many practical projects. However, owing to the limitations of traditional AMD (Active Mass Damper/Driver) control systems, the innovation of various actuators aimed at different application problems are still the hot topics for researchers. The defects of traditional hydraulic cylinder actuated AMD system include constitutional complexity, large volume, low energy efficiency and high cost etc. To overcome these problems, Direct Driving Volume Control (DDVC) system, also called as non-Valve hydraulic servo actuator, based on the hydraulic volume control principles is introduced into the AMD control system. The innovative DDVC based AMD system, abbreviated as DAMD, is the integration of three main parts: servo rotary motor, fixed volume pump, and hydraulic cylinder with double-end pistons. This paper discusses the mathematical models of controlling motor, energy transformation loops and hydraulic relations of cylinders with pumps, which forms up the whole electro-mechanical models of the DAMD control system. Through numerical simulations, the key influential factors on system dynamics are analyzed and optimized for scaled model experimental systems. At last, the dynamical characteristics of each component of the whole DAMD system as well as the improving strategy is studied and proposed. Based on the previous modeling and analysis, the equations of state for structure - DAMD system is developed, and numerical simulations for structure subjected to earthquake excitations with DAMD control system are studied. The results show that DAMD control system is feasible to replace traditional AMD control system to realize equivalent effective active control forces for structural vibrations.

7643-97, Session 10b

Analytical solutions for the optimal series tuned mass dampers

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Recently the authors proposed a novel configuration of tuned mass damper (TMD), in which multiple auxiliary absorbers are connected to the primary system in series. This so called series TMD has been proved to be more effective and robust than all other types of TMDs with the same mass ratio, such as the classic TMD, parallel multiple TMDs, multi-degree-of-freedom (DOF) and three-element TMD. The parameters of the spring stiffness, damping coefficient and mass distribution ratio among the auxiliary masses were optimized numerically using decentralized H2 and H∞ control methods. This paper studies analytical solution of the parameters optimization of the series TMD, using three different methods: fixed-point method, H∞ control and H2 control methods. The analytical expressions of the optimum are obtained with some approximations. Finally, the optimization results using different optimization methods are compared, together with the ones using numerical method previously done by the author.

7643-98, Session 10b

Innovative hybrid mass damper system for structural vibration control with energy harvesting capabilities

C. Zhang, Harbin Institute of Technology (China)

Based on the driving principles of linear motors used in magnetic suspended vehicles and the energy preserving techniques of fly-wheel batteries, as well as the AMD(Active Mass Damper/Driver) and passive TMD(Tuned Mass Damper) control techniques which have been widely studied and used in the field of vibration control for Civil Engineering structures, this paper proposes an innovative EHMD(Electro Hybrid Mass Damper) control system which has the multiple functions, such as electromagnetic driving, energy transforming and preserving capabilities etc. To be specific, during the small amplitude vibration of a tall building, the tuned EHMD control system can absorb and transform the vibration energy of the main structure into electrical energy and preserve it into system batteries. When the structure undergoes earthquake attacks or strong wind excitations, the stored energy can be released to drive the actuators to exert active control force onto the main structure to suppress its vibration. In this paper, one set of bench scale EHMD control system will be developed, and the parameter optimization and compatibility problems will be studied. Second, the mathematical models of “electro-mechanical-energy” relations for the system will be established. Then, thorough performance tests will be carried out to validate these theoretical models. Furthermore, the control algorithms considering control-structure-interaction effect will be proposed and experimentally verified through shaking table tests. At last, the stability of the EHMD system will be investigated. Upon properly design, the EHMD system can transform the unpleasant vibrations of the main structure into electrical energy and store them into the electro-chemical batteries which can be restored and reutilized. Recycling the waste energy into useful energy, the promising EHMD control system can also overcome some key problems of traditional active control systems, such as energy-dependent and time-delay etc.

7643-99, Session 10b

Parameter optimization and experimental verifications of displacement feedback based time delay compensation

C. Zhang, Harbin Institute of Technology (China)

Time delay is a more common effect in the vibration active control of structures, which not only degrades the performance of the control system but also introduce instability to the whole system. In this paper, the first part presents the stability analysis of a SDOF system with time delay feedback control loops. The purpose is to find the analytical solution of the maximum allowable delay constant, which can be used as a criterion for deciding whether or not to consider time delay compensation. Then, an innovative time delay compensation method, by actively increasing time delay constant when actual time delay is larger than the maximum allowable values, is proposed and numerically studied. The parametrical impact analysis and weight coefficient optimization proves that the system is conditional stable under Partial Displacement Feedback based active increasing time delay control strategy. At last, the experimental study is conducted on a single floor shear type frame structure model, where various excitations are input into the structure-delayed controller system. Both the numerical and experimental results demonstrate that the proposed time delay compensation control algorithm is effective in reducing the dynamic response of the structure and the system stability can be guaranteed.

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7643-101, Session 10b

Modeling and simulation of an amplified structural damping system in a seismically-excited truss tower

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Truss towers are a critical component in the communication infrastructure that serves as a lifeline to modern society. However, their flexibility combined with low inherent damping make them vulnerable to dynamic loads. Protecting tower structures can be achieved through the use of passive, active, or semi-active control devices. The purpose of the present work is to investigate a passive amplified structural damping system, specifically the scissor-jack damper, for controlling vibrations in seismically excited truss towers. In order to carry out the present investigation, models of both the truss tower and scissor-jack damper system are developed. For the truss tower, a 3D finite element model is first created in Matlab. To reduce computational effort during dynamic analysis, a bi-model method is employed to represent the 3D truss tower as a dynamically equivalent 2D model. The resulting dynamically equivalent 2D model is then represented by the lumped-mass model for the subsequent dynamic analysis in the Matlab environment. For the scissor-jack damper, a new formulation for the amplification factor equation of the device is presented. The new formulation accounts for the large deformations experienced by the device as a result of the large displacements present in the flexible tower during seismic loading. Accounting for these large changes in the device geometry is important as they have a significant effect on the amplification factor and the resulting damper forces applied to the tower. The 2D tower model and scissor-jack damper model are integrated in the Matlab environment to conduct numerical analysis. In order to capture the interaction between the structure and control device, it is necessary to solve for the value of the amplification factor and corresponding amplified damper forces at every time step. At each time step in the analysis, the displacements and velocities corresponding to levels at which concentrated masses are located are determined. These displacements and velocities are then used to calculate the displacements and velocities at remaining levels of the tower by applying pre-determined transformation matrices. Once the displacements and velocities at all levels of the tower have been determined, the displacement-dependent amplification factors of the scissor-jack devices, and velocity-dependent forces of the dampers, can be calculated. The resulting amplified force is then applied back to the structure to determine its response at the next time step. By repeating the process throughout the simulation, it is possible to capture the interaction of the device and structure, and evaluate the effectiveness of the scissor-jack damper for controlling vibrations in seismically-excited truss towers. The response of the tower with scissor-jack damper systems is simulated for four major earthquakes. The effectiveness of the scissor-jack damper is demonstrated through time-histories of the tower's second level displacement and acceleration responses. These results indicate that the system is effective in reducing both the displacement and absolute acceleration of the tower without exceeding practical limits on the damper's stroke capacity

Conf. 7644: Behavior and Mechanics of Multifunctional Materials and Composites IV

Monday-Thursday 8-11 March 2010

Part of Proceedings of SPIE Vol. 7644 Behavior and Mechanics of Multifunctional Materials and Composites 2010

7644-01, Session 1

Phasefield modeling of switching of polarization vortex in ferroelectric nanotubes

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By means of the phasefield method, we investigate the response of polarization vortices in ferroelectric nanotubes to a curled electric field. First, we describe the theory applied and it's numerical implementation with special attention to a non-curlfree contribution to the electric field. Next, it will be shown that there is a critical curled electric field magnitude, at which the switching of the polarization vortex takes place. As a result, a hysteresis type dependence of the toroidal moment of polarization on the vorticity of the electric field occurs. The details of this switching process are demonstrated and discussed.

7644-02, Session 1

The structure of the paraelectric: ferroelectric phase boundary interface

C. M. Landis, A. Kontsos, The Univ. of Texas at Austin (United States)

A continuum thermodynamics framework is used to model the structure of the paraelectric-ferroelectric interface in barium titanate. A phase-field modeling approach is applied and the model equations are solved by the finite element method. The crystallographic theory of martensite is used to compute the orientation of the austenite-martensite interface, i.e. the paraelectric-ferroelectric interface, along with the appropriate lamination scheme in the ferroelectric phase to enforce overall mechanical and electrical compatibility with the paraelectric phase. The crystallographic theory provides initial conditions for the finite element scheme, which is then used to relax the structure of the phase boundary and domain walls near the interface. Details of the energy and entropy changes across the phase boundary are presented

7644-03, Session 1

A finite deformation phase-field theory for ferroelectrics

W. Li, C. M. Landis, The Univ. of Texas at Austin (United States)

A phase field theory for ferroelectric incorporating finite deformation kinematics is presented. The general theory is presented first and terms commonly identified as Maxwell stresses are derived and discussed. The theory is Lagrangian as the governing equations are solved in the reference configuration. To investigate the consequences of the theory the standard free energy used in many phase field models for ferroelectric is adapted to the finite deformation framework simply by replacing the infinitesimal strain, the material polarization with their finite deformation counterparts. The finite element method is then implemented to numerically solve the governing equations and a model problem is investigated to compare the finite deformation theory with its linear kinematics counterpart.

7644-04, Session 1

Phase-field model with phase transformations of rhombohedral 95/5 PZT

W. Dong, C. Valadez, C. S. Lynch, Univ. of California, Los Angeles (United States)

Lead zirconate titanate (PZT) is a ceramic perovskite material that possesses piezoelectric, pyroelectric and ferroelectric properties. It is widely used in devices such as transducers, sensors, actuators, and capacitors. This paper will take a more in-depth look at the piezoelectric and ferroelectric properties of the 95/5 PZT. Experimental data is used to construct a phase-field model that shows a polar rhombohedral PZT being poled in the presence of an electric field and then depoled under hydrostatic compressive stress. The experimental data is used to provide the coefficients of the constitutive equations as well as for comparison with the model to determine its accuracy. The polarization is calculated using a phase-field model that looks at the lowest energy surface of a set of energy functions from different phases that are super-positioned.

7644-05, Session 2

New unifying concepts for modeling smart materials

W. S. Oates, Florida State Univ. (United States)

Field-coupled mechanics theories encompass a broad spectrum of material models aimed at predicting constitutive behavior of materials that deform in the presence of electric or magnetic fields, temperature changes, light or chemical exposure. Many of these materials can also act as sensors or novel adaptive structures that change their elastic, damping, or photonic properties. The majority of these models are focused on a specific type of field-coupled response or a particular composition. Limited work has been conducted on developing a unified theory that can predict the constitutive behavior of a broad class of smart materials. Such theories are useful for quantifying underlying field-coupled mechanics concepts to facilitate future materials development and design of adaptive structures. A new unified smart material modeling approach is presented and compared to compositions in the literature including ferroelectric materials, magnetostrictive compounds, and liquid crystal elastomers. The theoretical approach employs nonlinear continuum mechanics coupled to a set of order parameters that govern electro-magnetic behavior and liquid crystal phase evolution within an elastomer. Unifying concepts are obtained by determining a set of coupling parameters using finite deformation without introducing explicit phenomenological constants such as piezoelectric or magnetostrictive constants or liquid crystal phase transformations that are coupled to elastomer strain. Extensions of the model to more complex materials including multiferroics and photomechanical liquid crystal elastomers will also be discussed.

7644-06, Session 2

Reduced-order model development for high-order smart systems

S. F. May, R. C. Smith, North Carolina State Univ. (United States)

The use of finite element or finite difference techniques to discretize nonlinear smart material system models can yield full-order numerical models that accurately characterize the system dynamics but do so at significant computational cost. This can preclude the use of these full-order models for uncertainty analysis, sensitivity analysis, system design, or real-time control implementation. In this paper, we discuss

the construction of reduced-order system models using proper orthogonal decompositions (POD) with updates. Through the use of snapshots constructed from the full-order models, fundamental physics is retained while significantly improving efficiency for high-speed implementation. Using updates allows more flexibility when trying to balance the accuracy and the speed of the simulation. By updating the POD basis at specific times throughout the interval, we can increase the accuracy of the model by using a greater amount of the information given by the snapshots, while we can increase the speed of the simulation during times when using less information will still result in sufficient accuracy.

7644-07, Session 2

Adaptive nonlinear control design for hysteretic smart systems

X. Fan, R. C. Smith, North Carolina State Univ. (United States)

Ferroelectric and ferromagnetic actuators are being considered for a range of industrial, aerospace, aeronautic and biomedical applications due to their unique transduction capabilities. However, they also exhibit nonlinearities and hysteresis that must be accommodated in models and control designs to meet stringent performance criteria.

We investigate the problem of hysteresis control through the approach of adaptive nonlinear control designs which determine control signals that directly incorporate actuator nonlinearities.

In this paper, an adaptive nonlinear control architecture is developed for a class of smart hysteretic systems that models hysteresis using the homogenized energy model. The proposed control structure ensures the global stability of the entire system and achieves the stable tracking performance within a reasonable precision under certain conditions. Simulation results illustrate and validate the effectiveness of the proposed nonlinear control approach.

7644-08, Session 2

Finite element analysis of ferroelastic/ ferroelectric strain incompatibility in radially poled thick walled ferroelectric cylinders

S. Liu, C. S. Lynch, Univ. of California, Los Angeles (United States)

A linear analysis predicts that extraordinarily high electric fields are required to radially pole thick walled ferroelectric cylinders. In practice, the required poling fields are significantly lower than predicted by the linear analysis, but the process can result in cracking that originates at the outer surface electrode and propagates to the inner surface electrode, dielectric breakdown, and specimen destruction.. This occurs predominantly when the electric field is radially inward (positive electrode on the outside and ground on the inside). A finite element analysis using a multiaxial micromechanics based constitutive law is performed. Results indicate that polarization reorientation initiating at the inner surface and propagating outward significantly reduces the required poling field predicted using a linear analysis, and that the incompatibility of the poling strain with the displacement field of an expanding cylinder leads to a large compressive stress at the inner surface and a large tensile stress at the outer surface. It is postulated that microcracking at the outer surface coupled with a high potential at the outer surface associated with an inward pointing electric field attracts charge carriers through the fluid to the cracks and drives these charge carriers into the cracks, causing them to propagate as conducting cracks with resulting dielectric breakdown.

7644-09, Session 3

Mapping of domain structure in barium titanate single crystals by synchrotron X-ray topography

P. Potnis, J. E. Huber, J. P. Sutter, F. Hofmann, B. Abbey, A. M. Korsunsky, Univ. of Oxford (United Kingdom)

Imaging of domains is a key step in understanding the microstructure and hence the properties of ferroelectric single crystals. This understanding is essential for exploiting engineered domain configurations to achieve enhanced performance. In this paper, single crystals of Barium Titanate are observed by reflection topography using unfocussed monochromatic synchrotron X-ray light. A 10x10mm polished surface of an unpoled crystal was mapped to form a composite image, indicating a fine structure of a- and c- domains. By making use of the angular separation of the diffracted reflections and specimen rocking, the relative tilts between adjacent domains about two orthogonal axes were found. Angular resolution better than 0.1mrad in tilt measurements allowed the local elastic curvature of lattice planes to be observed. The resulting composite images show well defined boundaries between regions of distinct microstructure, and give an indication of the proportion of the domain types present. Over large regions of the crystal the domain structure was finer than the X-ray camera resolution of 6.5µm; AFM imaging of domains was then used to confirm the typical domain spacing. The results are interpreted in the context of models of compatible microstructure in tetragonal crystals using optical microscopy of etched crystals and AFM imaging to assist the interpretation. The technique shows promise for mapping fine microstructure in single crystals, through the use of high resolution X-ray cameras and is successful in revealing lattice orientation information that is not normally available in optical or AFM measurements.

7644-10, Session 3

A variational model of ferroelectric rank-2 laminate domain structures

N. Tsou, J. E. Huber, Univ. of Oxford (United Kingdom)

The equilibrium domain arrangements of ferroelectric single crystals are significantly affected by the applied loads and boundary conditions. Domain structures evolve towards a minimum energy (equilibrium) state. In this paper, a variational method, which minimizes a functional based on free energy and dissipation, is developed to model the evolution of several typical rank-2 laminate domain patterns in the tetragonal crystal system. Periodic laminates which satisfy domain compatibility across every junction where domains meet (not only compatible on average across their higher domain interfaces) are studied. These domain patterns include the well-known herringbone configuration and also a pattern consisting of an array of polarization vortex structures. The unit cells for both types of domain pattern dictate a set of domain walls whose positions may vary while maintaining the same topology. The positions of domain walls are treated as thermodynamic variables in the formulation, and the total dissipation rate is then a function of the velocities of the domain walls. By using this model, many features normally observed in ferroelectric single crystals can be reproduced, such as the dielectric hysteresis loop and butterfly loop. The characteristics of the hysteresis loop for different topologies, as well as under different applied loads and boundary conditions are discussed. The model is readily extended to apply to higher rank laminate structures and other crystal systems.

7644-11, Session 3

Fabrication and characterization lead zirconate titanate (PZT) single crystal film by PZT cubes alignment

Y. Lin, H. A. Sodano, Arizona State Univ. (United States)

Piezoceramic materials have attracted intense attention for sensing, actuation, structural health monitoring and energy harvesting applications in the past two decades due to their excellent capability in coupling the energy between mechanical and electrical domains. Among all the piezoceramic materials, lead ziconate titanate (PZT) has been extensive studied and used in academic and industry areas attributed to its high piezoelectric coupling coefficient. Single crystal

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PZT materials have higher piezoelectric coupling coefficients than poly crystalline ones attributed to the perfectly aligned dipoles in crystals. This paper will introduce a novel fabrication technique for a PZT single crystal like film by tape casting aligned PZT single crystal cubes fabricated by alternating electric field. A mixture of PZT cubes and additives composed of dispersants, binders and plasticizers will be cast in a Teflon mold and a high frequency alternating voltage will be applied through the thickness of the film. After the alignment, a sintering process will be carried out to remove all the additives and form a dense single crystal like PZT film. XRD and SEM analysis of the cross section of the final film with and without the alignment process will be performed and compared to show the success of the alignment. Finally, atomic force microscopy (AFM) will be used to directly measure the piezoelectric strain coupling coefficient of the aligned PZT cubes film and the results will show that the coupling coefficient is close to that of the single crystal PZT.

7644-12, Session 3

Triple-scale analysis and fabrication of new biocompatible MgSiO3 piezoelectric thin films

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The biocompatible piezoelectric materials, which can be applied to medical devices such as health monitoring system and drug delivery system, are strongly required. In this study, a new biocompatible MgSiO3 piezoelectric thin film is designed using a triple-scale analysis based on the first-principles calculation and fabricated using the sputtering method.

At first, a crystal structure and piezoelectric constants of biocompatible material, MgSiO3, were analyzed by the first-principles calculation. Next, a best substrate for MgSiO3 thin film was searched using the triple-scale analysis. Finally, piezoelectric properties of MgSiO3 thin film were calculated by finite element analysis based on the homogenization theory. As a result, lattice parameters of MgSiO3 crystal, a=b=0.3449nm and c=0.3538nm, and aspect ratio c/a=1.026 were obtained. And piezoelectric stress constants, e33=4.57C/m2 and e31=-2.20C/m2, were calculated. Additionally, it was indicated that [111] orientation of MgSiO3 on Au(111) substrate had a high possibility of epitaxial growth among other substrate candidates, and it had a high value of piezoelectric constants.

Next, MgSiO3 thin film was fabricated on Au(111) substrate using the sputtering method. Crystal structures were measured using the x-ray diffraction, and piezoelectric constants were obtained by the ferroelectric testing system. Diffraction angles of MgSiO3 were calculated by employing the numerically analyzed lattice parameters. Consequently, x-ray diffraction patterns of MgSiO3 showed a strong concentration at [111] orientation. This result coincides with numerical result. Furthermore, piezoelectric strain constant of MgSiO3 thin film, d33=145.93pm/V, was observed.

7644-13, Session 3

Domain switching in ferroelectric ceramics across morphotropic phase boundary

W. Tang, D. Fang, Tsinghua Univ. (China); J. Li, Univ. of Washington (United States)

A two-scale micromechanics model is developed in this paper to analyze domain switching in ferroelectric ceramics, using a probabilistic domain switching criterion based on energetic analysis. The microstructure of ferroelectric ceramics at two distinct length scales, domains and grains, has been carefully analyzed. The interaction at domain level is accounted for by energy minimization theory, while the fluctuation at grain level is analyzed using ellipsoidal two-point correlation function. The model has been implemented by Monte Carlo method, and applied to simulate the electric poling and mechanical depoling of Pb(ZrxTi1-x)O3 (PZT) ceramics across morphotropic phase boundary (MPB). The drastically different switching characteristics of PZT ceramics across MPB has been captured, and good agreement with experiments has been observed. The effects of the transformation strains and spontaneous polarizations are highlighted, confirming the proposition of Li et al. [2005. Domain switching in polycrystalline ferroelectric ceramics. Nature Materials 4, 776-781] that the strain compatibility plays a dominant role in domain switching in ferroelectric ceramics.

7644-15, Session 4

Thermomechanical characterization of environmentally conditioned shape memory polymer using nanoindentation

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Shape memory polymers (SMPs) are an emerging class of active polymers that have dual-shape capability, and are therefore candidate materials for multifunctional reconfigurable structures (i.e., morphing structures). However, the ability to reconfigure is currently limited by the material systems that can provide both rapid reconfiguration and long-term durability. To date, the SMPs have not been fully tested to work in relevant environments (variable activation temperature, fuel and water swell, UV radiation, etc.) required for Air Force missions. In this study, epoxy-based SMPs were conditioned separately in simulated service environments designed to be reflective of anticipated performance requirements, namely, (1) exposure to UV radiation for 125 cycles, (2) immersion in jet-oil at ambient temperature, (3) immersion in jet-oil at 49oC, and (4) immersion in water at 49oC. Subsequently, the novel high-temperature indentation method was used for in situ measurements of shape recovery ability and temperature-, time- and rate-dependent mechanical properties of conditioned SMPs.

The shape recovery tests were conducted based on both low-temperature (<Tg, where Tg is the glass transition temperature) and high-temperature (>Tg) indentations. Both sharp tip and a blunt tip were used for the indentation to generate low and high level stresses, respectively. Elastic and viscoelastic properties of the environmentally conditioned SMPs were measured. Results show that environmental conditions have affected both the shape recovery ability and mechanical properties of the SMPs. Conditioned SMPs generally exhibit higher moduli and creep exponents in comparison with an unconditioned one. During free recovery, the indentation impressions of all SMPs disappeared as temperature reached above Tg. However, the surfaces of some conditioned SMPs were unable to fully recover to their original profiles for a given time.

7644-17, Session 4

Development of a McKibben artificial muscle using a shape-memory polymer

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McKibben artificial muscle actuators have many attractive features such as small, lightweight, simple, soft and flexible. When these actuators are applied to robotic joints, the joints are driven by pairs of the actuators located antagonistically for the increase of the joint stiffness. However, the force is not so large and these actuators have non-linear characteristics and hysteresis. Therefore, the objective of this study is to develop a McKibben artificial muscle using a shape-memory polymer (SMP). SMPs can be deformed above their glass transition temperature (Tg) by applying a small load. They maintain their shape after they have been cooled to below Tg. They then return to the predefined shape when heated above the glass transition temperature. Exploiting these characteristics, we coated the braided mesh shell of a commercial McKibben artificial muscle and made a prototype of the McKibben artificial muscle using the SMP. When this new actuator is warmed above Tg, the SMP can deform. Then, when the internal

bladder is pressurized, the actuator shortens and/or produces a load if it is coupled to a mechanical load. After the actuator becomes the desirable length, the actuator is cooled to below Tg and the SMP can be fixed in a rigid state even if without a air supply. Consequently, this actuator can maintain its length more rigidly and accurately. In this study, we tested the fundamental performance of this prototype. The experimental results of a preliminary proof-of-concept investigation conducted on this prototype confirm the feasibility of this new actuator.

7644-96, Session 4

Jetsum: SMA actuator based undersea unmanned vehicle inspired by jellyfish bio-mechanics

S. Bressers, Virginia Polytechnic Institute and State Univ. (United States)

Previously, we have reported an undersea unmanned vehicle (UUV) inspired by the locomotion of medusa jellyfish, termed JetSum [Proc. SPIE 7287, 72871G (2009)]. The design of JetSum utilized shape memory alloy (SMA) actuators in wire form to replicate the two-phase contraction-relaxation cycle of natural jellyfish locomotion. In this paper, we report on design modifications that address problems related to performance of locomotion and power consumption. The changes include implementation of a full continuous bell, bolstering critical sealing junctions, and optimization of input signal. A LabVIEW controller program was developed to automate and optimize the driving of JetSum enabling optimization of performance. In particular, the response of the SMA actuators, and consequently performance of the vehicle, was investigated by varying the magnitude, frequency, and duration of the input signals. JetSum locomotion in underwater conditions was recorded by using a high-speed camera and analyzed with image processing techniques developed in Matlab. The results show that JetSum was able to achieve instantaneous velocities up to 7 cm/s and instantaneous accelerations up to 19 cm/s2.

7644-18, Session 5

Phase transformations and shape memory effects in finite length nanostructures

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In a number of nanostructures, the energy as a function of lattice spacing exhibits two distinct minima that correspond to fcc and bct phases. Such nanostructures may also exhibit shape memory effects which has been confirmed by both experimental and computational methodologies.

While many theoretical results up to date have been obtained for infinitely long nanowires, including those obtained with ab initio calculations, the question has remained on whether phase transformations is a generic effect for the same material-type nanowires of finite length. Although there has been mounting evidence towards a positive answer to this question, comprehensive studies of nanowires of finite length are limited due to the fact that the methodologies applied for their studies are computationally expensive. In addition, there are a number of questions that remain open at a large extent, including questions related to temperature-dependent phase stability.

In this contribution, we develop a relatively simple and computationally inexpensive model to study phase transformations in finite nanostructures with our major focus given here to nanowires of finite length. We show that in the latter case, the models describing shape memory effects at the mesoscopic level can be reduced to a 2D case (and in the case of nanowires of infinite length, to the 1D case). We study the cubic-to-tetragonal transformations in which case the 2D analogue of the model describes the square-to-rectangle phase transformations. Several representative examples of mechanical behavior of nanowires are shown for the nanowire length range of 30-200 nm and for different diameter-length ratios.

7644-19, Session 5

Mechanical characterization of Ni-Ti-Hf high temperature shape memory alloys

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Shape Memory Alloys (SMAs) have the ability to produce very high actuation strain, stress and work output as a result of reversible martensitic phase transformations; however, their high temperature commercial applications have been limited due to their low transformation temperatures (below 100°C) or unsatisfactory shape memory properties. In order to overcome these handicaps, NiTi is alloyed further with ternary elements such as Pd, Pt, Au, Hf and Zr to make it display remarkable SM properties at higher temperatures. Among those, Ni-Ti-Hf is the most promising alloy family due to its low production cost. On the other hand, Ni-Ti-Hf suffers from unstable shape memory behavior and lack of superelasticity due to its low strength and high transformation hysteresis.

In this study, thermo-mechanical treatments have been utilized to tailor the microstructural, mechanical and shape memory properties of the Ni-Ti-Hf high temperature shape memory alloys. Extensive mechanical characterization studies have been conducted to determine the shape memory behavior of thermomechanically treated NiTiHf alloys. It has been revealed that transformation temperatures and mechanical response can successfully be adjusted by precipitation formation. Precipitates can alter both the composition and the strength of the matrix where stable superelastic and shape memory behaviors with low transformation hysteresis at temperatures above 100 C can be observed in NiTiHf alloys.

7644-20, Session 5

Passive damping of composites with embedded shape memory alloy wires

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Shape memory alloy (SMA) integration as thin wires into host composite materials is reaching potential applications as actuators and damping devices in a variety of industries. In this study, NiTi wires were embedded during the infusion processing of woven CFRP composite plates with the purpose to passively increase their damping.

Two types of NiTi wires, having the same diameter of 0.2 mm, were considered, one superelastic at room temperature, the other one martensitic. For the first one, a martensitic transformation was induced by applying a pre-strain of 2.5% before embedding the wires. The coexistence of austenite and martensite provides damping through the mobility of boundaries between the two phases. For the second type of wires, the enhancement of damping was based on the presence of martensite.

The passive damping effect produced by the SMA wires was evaluated from free vibration tests on composite beams, neat or with increasing amounts of SMA wires. Resonance frequency and damping ratio were measured as a function of temperature. Improvement in damping was verified, at room temperature, for both types of SMA wires and was observed to be dependent on vibration amplitude. For small-amplitude free vibrations, martensitic wires present more interest as they provide an increase in damping of around 50 % for a volume fraction of wires of 5%. The effect changes for temperatures close to the transformation temperature of the wires. Practical guidelines will thus be given as a function of the actuation temperature, allowed density increase and manufacturing practice.

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7644-21, Session 5

Characterization of indentation response and shape memory surface morphology of Ni-Ti-Hf-Cu and Ni-Ti-Hf-Pd high temperature shape memory alloys

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Instrumented indentation technique is one of the most commonly used testing methods to characterize the mechanical properties of a wide range of materials at small scales. In this study, a systematic investigation is conducted on the indentation by Vickers and spherical indenters and two-way shape memory surfaces in subsequent thermal cycling of thermally treated NiTiHfCu and NiTiHfPd high temperature shape memory alloys (HTSMAs). Indentation depth and work recovery ratios as functions of indentation geometry, load, rate and depth, and thermal treatment are determined to reveal the shape memory and superelastic behavior of these alloys. Moreover, by employing optical profilometry method, the change in indent geometries during temperature cycling is revealed. It has been shown that thermally reversible surface protrusions, based on the two-way shape memory effect, can be induced and their shape can be controlled at temperatures higher than 100 C. This may lead to many potential applications where controllable surface roughness at high temperatures is desired, such as MEMS, surface morphing and tribological systems. It has been shown that indentation and optical profilometry techniques provides very useful information on the mechanical behavior of HTSMAs at micro scale for high temperature applications where NiTiHfCu and NiTiHfPd alloys could be considered as excellent candidates in variety of high temperature applications.

7644-22, Session 5

3-D finite element analysis of indentation recovery due to the shape memory effect

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The rapid growth of micro-scale devices in current technology markets creates a drive to explore the potential of existing technologies to enhance the effectiveness and capability of these devices. Shape Memory Alloys (SMAs), long used as actuators in a variety of applications, exhibit behavior that demonstrates great promise for micro-actuation use. Thus, incorporating the unique properties of these materials into new actuation applications is a focus that merits extensive research. One outgrowth of this is the study of indentation recovery due to the shape memory effect. Recent observations of indentation recovery in SMAs indicate that these repeatable deformations suggest a strong potential for micro-actuation use. Prior and current experiments have examined indentation recovery and tested its actuation ability, motivating further study using analytical methods. This work discusses the 3-D Finite Element Analysis (FEA) of the shape memory effect in an SMA material subject to indentation using a new SMA transformation-plastic yield constitutive model.

Experimental observation of the shape memory recovery associated with indentations in SMAs is accomplished with a three-step procedure. First, an SMA specimen is indented with a spherical or cylindrical micro-indenter. The surface layer of the material is then removed to make the new surface layer flush with the maximum depth the indenter achieved in the material. The final step involves the heating of the indented SMA material to generate a surface protrusion due to the austenitic phase transformation; subsequent cooling causes the protrusion to retract and the surface to return to its pre-heating state via the martensitic phase transformation.

Numerical analysis of this experimental procedure is used to examine the mechanisms underlying the shape memory effect that contribute to the indent recovery. In particular, the deformation of the SMA material necessitates the study of the influence of plasticity on the indent recovery. The Abaqus FEA Suite is used for this analysis, and the material response is defined by an SMA transformation-plastic yield constitutive model implemented in a user material subroutine. It is shown that the irrecoverable plastic zone formed during indentation can help drive the subsequent shape memory effect in the material. The analysis process mimics the three experimental steps; for the first, the indention of the material is simulated using axisymmetric or plane-strain assumptions for the simulation of spherical or cylindrical indenters, respectively. The second step simulates the planarization of the material surface to be flush with the maximum indentation depth. This is accomplished by removing the elements above this depth from the analysis. The third step models the transformation of the SMA and the protrusion and subsequent retraction of the indent during heating and cooling, respectively. The results of this analysis are compared to experimental data; it is observed that the phenomena of protrusion and retraction in planarized indentations can be effectively modeled using these advanced analysis tools.

7644-23, Session 5

Processing and characterization of composite shape memory alloy (SMA) thin film structures for microactuators

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The high work to volume ratio and the stress recovery of Shape Memory Alloy (SMA) thin films with temperature makes them an ideal choice for microactuators. However, these materials have not gained widespread acceptance due to issues associated with phase transformation. Primary concerns are rapid change in stress at the transformation temperature giving the actuator a step function like response and a significant shift in transformation temperatures due to a wide hysteresis. In the present research, TiNiCu (53.59at%Ti, 39.05at%Ni), TiNi (50.32at%Ti) and TiNiHf (39.56at%Ti, 48.63at%Ni) composite SMA thin films that display close to linear stress temperature behavior (slope: 2-7 MPa/C) with high stress recovery (300-550MPa), wide transformation range (60-130C) and low hysteresis (10-30C) were fabricated. Properties were achieved through the deposition of SMA thin films with varying composition in a layered (composite) format on Si wafers. The TiNi+TiNiCu composite exhibited a two-step transformation (slopes of 2.5 and 3.9 MPa/C) without a significant impact on stress recovery. Displaying identical recovery stresses, the TiNiHf film possessed a 65C transformation range and the TiNiHf+TiNi composite exhibited a wider range of 120C. In addition, the hysteresis dropped by 30C for the composite compared to a single layer TiNiHf film. For the annealing conditions identified, a three-layer composite structure exhibited the best characteristics (transformation range of 130C and a recovery of 550 MPa) with a significant drop in hysteresis values compared to single and two layer films. A strong correlation between deposition conditions, annealing parameters and transformation characteristics was observed for all the SMA films.

7644-24, Session 5

Low-hysteresis in Ti50Ni50-xPdx alloys

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In previous work [1,2,3] a relationship between the hysteresis and the middle eigenvalue $\lambda 2$ of the distortion matrix was found, with the size of the hysteresis dropping sharply near $\lambda 2 = 1$. The condition $\lambda 2 = 1$ is a necessary and sufficient condition for a perfect, untwinned interface between austenite and martensite. Recent work also links the size of hysteresis to fatigue resistance of NiTi alloys.

In earlier work [3] $\lambda 2=1$ was achieved for the systems TiNiPd, TiNiPt and TiNiAu and this coincided with the minimal hysteresis in all three cases. Furthermore, untwinned, atomically sharp interfaces between the austenite and martensite in Ti50Ni40Pd10 were observed by high resolution electron microscopy [4] and fully transformed martensitic alloy Ti50Ni39Pd11 showed unusual large twinless plates [5]. When

the size of the hysteresis was plotted vs. λ2, there was a sharp drop in all three cases. The minimal hysteresis of those studies occurred for Ti50Ni39Pd11 and was ~12 degree Celsius. Since the drop is so sharp, it is possible that this is not actually the minimum hysteresis. The present study was designed to define the minimum. In this paper, we report carefully measured lattice parameters and transformation temperatures of Ti50Ni50-xPdx, 8.5≤x≤11, using increments Δx = 0.25, and new high resolution images of these alloys. The minimum hysteresis measured by DSC (differential scanning calorimetry) among these alloys is found to be ~6 degree Celsius for Ti50Ni40.5Pd9.5. Hysteresis vs. λ2 appears smooth, rather than cusp-like, at this tolerance level.

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7644-25, Session 5

Simulation of austenite-martensite interface in microstructures and hysteresis

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We utilize the nonconventional multivariant model to simulate the Austenite-Martensite interface in microstructure. Separation of length scales between the Austensite-Martensites and the twinned-Martensites are critical here. An innovative two-scale algorithm has been introduced to deal with the problem. Microstructures of common crystal systems are simulated using this approach, and good agreement with experimental observations is obtained. We then attempt to verify the thermal hypothesis in microstructure raised by R.D. James on whether the middle eigenvalue being zero is a critical criterion for thermal hysteresis in the linearized theory.

7644-26, Session 5

Modeling and experimental study of simultaneous creep, plasticity and transformation of high temperature shape memory alloys during cyclic actuation

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High Temperature Shape Memory Alloys (HTSMAs) represent a class of Shape Memory Alloys (SMAs) with transformation temperatures greater than 100ºC [1, 2]. These alloys are formed by alloying binary NiTi with a third alloying element such as Platinum, Palladium, Gold, Hafnium or Zirconium [3, 4]. Thermally induced transformation behavior of these alloys under load has been widely studied to understand their actuation performance [5-8]. More recent efforts have focused on improving the formability of these alloys [9]. As a consequence of their high transformation temperatures, the HTSMAs can be exposed to a temperature regime where creep behavior can occur simultaneously during the transformation. The creep behavior of ternary NiTiPd and the interaction between transformation and creep occurring simultaneously has been recently studied in compression [10] and a thermodynamic model was developed to capture this interaction. However the experimental and modeling effort were limited to one actuation cycle.

7644-27, Session 6

A 3D model for the dynamical sensing response of Galfenol with applications to energy harvesting

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A 3D model for the dynamical sensing response of magnetostrictive Galfenol is developed. The model calculates the fraction of magnetic moments oriented along each of the energetically preferred directions of the crystal as a function of time, which is used to determine the total magnetization versus time. The model is appropriate for axial and shear stresses and magnetic field biases applied at various orientations.

In a previous work (P. Weetman and G. Akhras, Appl. Phys. Lett. 95, 072504 (2009)), a 1D dynamic sensing model was developed using a self-consistent rate equation technique. This model was only appropriate for cases where a single stress and a magnetic field bias are both applied along an axis about which rotational symmetry can be approximated. In order to simulate the dynamic sensing response for arbitrary geometries and loading conditions, the model is expanded to 3D.

Results are presented for the sensing response for two systems: a Galfenol crystal with 19% at. wt. Ga oriented along the axis, and a Galfenol crystal with 18% at. wt. Ga oriented along the axis. The second system cannot be modeled in 1D, calculations have to be performed using the 3D model only. Finally, as an example application, the sensing system is incorporated into a simple AC energy harvesting system. Extra non-linear effects due to a magnetic field induced by the pick-up coil must be incorporated into the self-consistent model. Output voltage versus applied stress is calculated for the first sensing system.

7644-28, Session 6

Modeling the magneto-elastic interactions of magneto-sensitive composites

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Our previous experimental studies of Magnetorehological Elastomers (MREs), composite materials made up of ferromagnetic particles suspended in polymer matrix, showed that they are capable of changing their mechanical properties in response to an external applied magnetic field. These field induced change in properties are attributed to the magnetic interaction between the ferromagnetic particles as well as the accompanying elastomeric response of the polymer matrix, which results in magneto-elastic effects. One of the magneto-elastic effects is the change in dimension or shape of the material due to applied magnetic field i.e., magnetostriction. Experimental evidence shows that the magnetostriction of MREs is comparable to (or in some cases higher than) other common giant magnetostrictive alloys such as Terfenol. In addition, the magnetostriction of MREs displays hysteresis, an effect that results from some form of dissipation of energy during the magneto-elastic interaction. MREs can also change their stiffness when exposed to magnetic field as a result of the same magneto- elastic effect. Applications utilizing the magnetostrictive property of MRE are few; however, it is believed that they can be used for actuators and sensors. In order to expand the possible application of these materials, their experimental and theoretical understanding is of paramount importance. For that purpose, the main focus of this study is to model magnetostriction of MREs using thermodynamics and micromechanics theories. An effort will be made to incorporate the hysteresis effect into the model unlike the preexisting mathematical models of these materials by making use of thermodynamic internal variables that take

into account the dissipation mechanism for the hysteresis effect. The results from the developed model will be compared to our experimental results.

7644-29, Session 6

Power generating by high pulse mechanical stimulation of magnetic coupled NdFeB and Terfenol-D

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Rising requirements for a new constructions, devices and machines force engineers to monitoring them all day long. An atractive solution seems to be applications of wireless sensors. However, there is a barrier limiting their apply which is the need to supply them with an electrical power over extended period of time without using addtional wiring or batteries. The potentail solution which can provide this problem seems to be an energy harvesting. Most methods of obtaining the energy from the external sources e.g. vibrations, is to use piezoelectric materials. However, the amount of energy generated by piezoelectric materials is smaller than most electronic devices need. Therefore, new method to generating a pulse of energy and conditionig for other loads devices must be developed. This paper proposes a new energy harvesting device based on magnetostrictive material. In course of experiments with using Terfenol-D rods as actuators and sensors it has been observed interesting phenomenon. Mechanical stroke (e.g.energy beetwen 10J and 100J in infinite time) to magnetic core based on Terfenol-D rod (diameter 8mm, length 50 mm), NdFeB permanent magnets and coil allowed get electric power signal enough to supply device of 100 Ohm load on their active state (tipical low power controller). In comparison to the same magnetic circuit build with other typical ferromagnetic materials e.g. Armco iron, showed effect 10 times lower or none. Tests and experiment showed important role of coupling Terfenol-D and NdFeB permanent magnets, their configuration and variable coil parameters determined this effect. Regard to the results authors proposed construction of new impulse harvesting method based on Terfenol-D material for low impedance load.

7644-30, Session 6

Image analysis of the microstructure of pseudo-1-3 magnetostrictive composites

X. Dong, Dalian Univ. of Technology (China); X. Guan, Harbin Institute of Technology (China); J. Ou, M. Qi, Dalian Univ. of Technology (China)

Due to the shape anisotropy of the particles, applying a magnetic field during the manufacture process of polymer-bonded Terfenol-D could orient the major axis of the particles along the field direction and form a pseudo-1-3 type composite. Compared to 0-3 composites prepared without magnetic field, 1-3 type shows much larger magnetostrictive performance, which has been proved by several experimental studies. In this paper, the microstructure of the magnetostrictive composites prepared under different magnetic field was observed and analyzed. Magnetostrictive composites were fabricated using Tb0.3Dy0.7Fe2 powder and a three-part unsaturated polyester resin with a low viscosity of 0.2 (25oC) and a high elastic modulus of 3Gpa. The shape of the particles is irregular, and the distribution of the particle size is in the range of 30μm to 500μm. Comparison of Gaussian fitting curves of the angles between the major axis of particles and the arrangement field direction among all the three composites shows the tendency of the angles converge at 0o increasingly significant with increasing arrangement field. It indicates the microstructure along the field direction approximates 1-3 architecture with increasing arrangement field, which is responsible for the changing magnetostrictive properties with the magnetic field applied during the manufacture of magnetostrictive composites.

7644-31, Session 6

Finite element modeling of magnetostrictive thin film actuator considering the nonlinear magnetic field for MEMS

H. Lee, C. Cho, Inha Univ. (Korea, Republic of)

For the design and optimization of the magnetostrictive actuators, numerous theoretical and numerical models have been proposed. Although articles on modeling of magnetostriction by using generic algorithm, artificial neural networks or Preisach hysteresis model have reported by several authors, most of the previous studies are devoted to the numerical model, especially finite element model. On account of extensive researches in this area, various electrical and mechanical devices can be analyzed using the finite element technique. Also, some of them have been successfully commercialized. But the direct application of these finite element models to the magnetostrictive MEMS devices poses some serious problems. Firstly most finite element models are concerned with the longitudinal motions of Terfenol-D rods. Thus they cannot be effectively used for the magnetostrictive thin films which have the shape of membrane, or plate. Secondly, although there is an exception, they also assume linear properties. Since it is usual to apply high external magnetic field to magnetostrictive MEMS devices to obtain high strain outputs, nonlinear magnetic properties with magnetic field should be considered. Therefore, specific finite element tools are needed to design MEMS devices utilizing magnetostriction as a deriving principle, and analyze their performance.

In this work, two-dimensional and three-dimensional finite element model considering nonlinear magnetic properties are presented. Examples are solved to verify the validity of the developed program. To validate this model experimentally, a flexible magnetostrictive actuator is fabricated by depositing a thin film of NiFe on a flexible polyimide substrate. The magneto-mechanical characteristics of the actuator are measured, and the results of magnetostriction using suggested numerical FE model are compared with the experimental results. Finally, the results are discussed.

7644-33, Session 6

Magnetostrictive properties of $Tb0.24Dy0.76Fe_{2-x}Ni_x$ thin films for wireless micro actuators and application to array type micro transporter

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In this paper, the effect of Ni on the magnetic, magnetomechanical properties of the Tb0.24Dy0.76Fe2 system for wireless micro actuator with the effect of deposited film thickness of TbDyFeNi on silicon substrate were investigated. To examine the properties, Tb0.24Dy0.76Fe2-xNix, (x=0, 0.5, 1.2, 2.0) films were sputter-deposited on the silicon substrate with the condition as: Ar gas pressure of below 1.2E-9 torr, DC input power of 200W and heating temperature of up to 300°C. After the sputter process, magnetization and magnetostriction of each sample were measured. X-ray diffraction studies also carried out to certificate the film structure and thickness of the sputtered film. From the investigation, unique property was used to build a novel wirelessly controlled array type micro transporter. The micro actuators with film thicknesses of 0.1, 0.5, 1, 2 μm were fabricated by silicon micromachining with selective DC magnetron sputtering techniques. For the operation, the array type micro transporters have comb shape with each branch size of 150 μm × 800 μm × 50 μm and TbDyFeNi was sputtered on the back side of the each branch for the actuation. Each branch was attracted by externally applied magnetic fields up to 5kOe and motion of the branches made transportation movement. As an application result, transported distances of the actuators to external magnetic fields were observed.

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7644-16, Poster Session

A preliminary study on effect of gamma radiation on shape memory polymer composite filled with carbon nanotube

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Abstract: As a new type of smart material, shape memory polymer (SMP) receives increasing attention in recent years. SMP has found various applications including heat-shrink connector, biomedical devices and deployment structure, etc. However, SMP materials have not fully exerted their technological potential applications especially in spatial structure, largely due to the limited anti-irradiation performance for polymer materials. Hence, some gamma radiation shielding additives are added into shape memory polymer to prepared SMP composite to increase its anti-irradiation property. In this paper, in addition to the fabrication of SMP composite filled with carbon nanotube, the effect of gamma radiation on thermo-mechanical properties of the composite were investigated. Results show that glass transition temperature (Tg) determined by DSC decreased by 5°C after the irradiation. According to DMA test, the gamma radiation has a slight influence on storage modulus, loss modulus and tan delta, respectively. No considerable change was found both in tensile strength and elongation at break after the gamma radiation due to the tensile test. Finally, the shape recovery ratio is near 100% for the composite both with and without the gamma irradiation. Based on the above results, it can be demonstrated that the composite prepared in the study possesses not only good thermo-mechanical properties but unique anti gamma radiation performance, which shows potential application of aerospace fields.

7644-52, Poster Session

EMI shielding performance study of tri-layer nano stealth composites

D. Song, Harbin Institute of Technology (China)

Due to the great progress of stealth technology in recent years, the stealth materials preparation has become an active research field. Nano stealth composites are specially promising in stealth materials. Among of these nano composites, CNTs and ferromagnetic nano powder cause more concerns because of their excellent EMI shielding characteristics. In this paper, a method for preparing tri-layer nano stealth composite film is proposed. Using H2SO4, HNO3 mixture for MWCNTs carboxylation, dispersant CTAB is added into surface-treated CNTs, nano Fe and nano Fe3O4 respectively. These three mixtures are dispersed by ultrasonic vibration so that they form homogeneous films in EPOXY matrix. Vector network analyzer is utilized for EMI SE measurements. According to experiment data, EMI shielding performance curves are generated when CNTs vary from 4%-10%wt, nano Fe 10%-15%wt, nano Fe3O4 15%-30%wt respectively in the frequency bands of 3.22-26.5GHz. Simultaneously, variation trends of these curves are analyzed. A new type of multi-layer nano stealth composite film is fabricated by superposing the three films prepared above, with nano Fe layer as matching layer, CNT layer as absorbing layer, and nano Fe3O4 layer as the reflecting layer. Adjusting the thickness and the content components to change the parameters such dielectric constants, optimal configurations are obtained with consideration of peak value, the EMI SE frequency bandwidth and the electrical conductivity respectively. These experiments improve the adaptability of the film in various working conditions. Experiment curve fits to computing curve referencing multilayer material theory of transmission lines. It demonstrates the effectiveness of the preparation method of tri-layer nano stealth composite film.

7644-73, Poster Session

Nonlinear bending response of Terfenol-D/PZT laminated devices under electromagnetic fields

K. Mori, F. Narita, Y. Shindo, Tohoku Univ. (Japan)

Magnetostrictive alloys and piezoelectric ceramics play a significant role as active electronic components in many areas of science and technology, such as smart structures and devices. Tb0.3Dy0.7Fe2 (Terfenol-D) is a highly magnetostrictive alloy of iron and rare-earth metals, and has a unique advantage over the other smart structures and devices. In recent years, it has been found that the laminated composites of Terfenol-D and Pb(Zr, Ti)O3 (PZT) ceramics possess superior magnetoelectric (ME) effect. One of the limitations for practical use of the composites of Terfenol-D alloys and PZT ceramics is nonlinear behavior. In order to optimize the performance of the Terfenol-D/PZT laminated devices, it is important to understand the nonlinear behavior of the devices under electromagnetic fields.

In this work, we present the nonlinear bending response of Terfenol-D/PZT laminated devices under electromagnetic fields in a combined numerical and experimental investigation. The fabricated devices consist of thin Terfenol-D and soft PZT layers. The magnetostriction of the Terfenol-D layer bonded to the surface of the PZT layer was measured as a function of applied magnetic field. A nonlinear finite element analysis is also carried out, and the second-order magnetoelastic constant in Terfenol-D layer bonded to the PZT layer was evaluated. The nonlinear deflection and internal stresses for the Terfenol-D/PZT laminated devices under applied electromagnetic fields are then discussed. In addition, the induced voltage due to applied magnetic field and induced magnetic field due to applied electric field for the devices are examined.

7644-75, Poster Session

Modeling and simulation of corrosion mechanism for glass fiber reinforced plastic in sea water

J. Yin, Harbin Institute of Technology (China)

Through summarizing and analyzing the physical corrosion theories of polymer, a theoretical model is constructed to depict the relationship between relaxation time with temperature, stress and humidity. The correlation between physical corrosion behavior and external factors is predicted from semi-experimental profile. In sequence, the morphology of polymer and fiber was investigated by the scanning electron microscopy (SEM) in comparison with that of non-immersed samples. The dynamic mechanical thermal analysis (DMTA) methods were used to study the evolution of thermomechanical properties against immersed time. It is found that the glass transition temperature (Tg) and storage modulus were significantly reduced with immersion time increase. Then the hardness, tensile strength and bending strength of GFRP were tested by their corresponding mechanical measurements.

7644-76, Poster Session

A phenomenological rate-related model for the super-elastic shape memory alloy

B. Zhou, Harbin Engineering Univ. (China)

There is increasing interest in using superelastic shape memory alloys (SMAs) in civil, mechanical and aerospace engineering, attributed to their large recoverable strain, high damping capacity, and excellent fatigue property. Experimental phenomena show the mechanical behaviors of SMA is related to loading rate. In this study a new rate-related constitutive model of SMA is developed based on Zhou's constitutive model which ignores the dependence of mechanical behaviors of super-elastic SMA on the loading rate. Numerical

simulations and comparison with the previous experimental results show that the new constitutive model well predicts the mechanical behaviors of SMA and reflects the influence of loading rate.

7644-77, Poster Session

Simulation models for design and production of active structural parts with deformed piezoceramic-metal-compounds

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This paper deals with simulative investigations of piezo-metal-compounds which are developed within the Transregional Collaborative Research Centre “Production technologies for light metal and fiber reinforced composite based components with integrated piezoceramic sensors and actuators” with the promotion of the German Research Foundation.

One concept is the integration of laminar piezo-modules in structural parts during the forming process. The compound of sheet metal layers and piezo-module is formed by deep drawing, stretch forming and 3-point bending.

To locate the limits of formability of the piezo-modules information about strains and stresses are necessary. On the other hand detailed finite-element-models with a discretization in the dimension of the piezo material are not suitable for forming simulation concerning the size of the simulation model.

Due to the periodic structure of the piezo-modules the simulation method of representative volume elements can be used to homogenize the material parameters. The estimated homogenous material parameters show a good conformance with measurements published by the manufacturer of the piezo-modules. With the homogenized material parameter, the piezo-module can be integrated in the forming simulation as simplified model.

In order to achieve the real strains and stresses of the piezo material the strains/stresses obtained with the homogenous material have to be superimposed with the phase concentrations from the unit load cases. Special consideration has to be given to the bending load due to the forming of the sheet metal.

Verification of the simulative determined loading of the piezo-modules is done by comparison with damage images achieved by computer tomography.

7644-78, Poster Session

Characterization of a Pt-core PZT fiber/Al matrix composite

M. Richeson, K. M. Mossi, Virginia Commonwealth Univ. (United States); J. Kunikata, H. Asanuma, Chiba Univ. (Japan)

The objective of this study is to characterize a piezoelectric composite sensor/actuator fiber. The composite is manufactured of a platinum-core lead zirconate titanate (PZT) fiber (diameter: 0.22 mm) inserted into an aluminum matrix, which serves the purpose of being the ground terminal. Fabrication of the composite is accomplished in three steps. First, a stainless steel wire (diameter: 0.35 mm) is used to press an indentation into an aluminum plate (thickness: 0.4 mm), into which the PZT fiber is inserted. A sheet of copper foil (thickness: 0.01 mm) is used as an insert material to prevent destruction of the PZT fiber during hot pressing. Next, a second aluminum plate (thickness: 0.2 mm) is placed on top of the first and the two are hot pressed together at 873 K, 2.2 MPa for 40 minutes. The composite is then cut to the dimensions 30 mm x 1.8 mm x 0.55 mm and poled at 300 V for 30 minutes. The finished sample is soldered to a connector for ease of testing. This study characterizes the described compoiste by testing its impedance, capacitance, voltage sensitivity response to vibrational inputs, and deformation due to electrical input. Results show a capacitance in the 500-700 pF range throughout the frequency spectrum (100 Hz to 10 MHz), but a sharp drop off for frequencies greater than 10 MHz. Electrical response to vibrational inputs has also been investigated using a Macro Fiber Composite (MFC) to provide the input vibrations. The MFC was fixed to a solid surface and the composite fixed to the MFC’s other surface, to maximize transmission of vibrations to the composite. Operating the MFC with various wave functions 200-800 Vpp, 1-5Hz, the composite demonstrated a response in the mV range. Response was notably higher, reaching 200 mVpp for square and ramp input waveforms. On the other hand, sine wave inputs resulted in much lower voltage responses from the composite (approximately 1 mVpp). In addition, displacement curves with applied voltage are also measured.

7644-79, Poster Session

Bio-inspired unmanned undersea vehicle

C. F. Smith, A. Villanueva, S. Priya, Virginia Polytechnic Institute and State Univ. (United States)

Inspired by the sub-umbrella structural and actuation features of jellyfish, artificial bell designs were created mimicking the meso-scale details and analogous propulsion mechanism. Artificial jellyfish unmanned undersea vehicle (UUV) was fabricated consisting of silicone as the matrix material and shape memory alloy (SMA) as the actuation material. UUV was characterized for its performance and tailored to achieve vertical motion. SMAs were selected for actuation because they are simple current-driven device providing large strain and blocking force. However, electrical power requirements were found to be quite high in the underwater conditions. It was identified that by including “joints” in the structural material forming the bell the overall power requirement can be reduced as it lowers the resistance to compression. An analytical model was developed that correlates the deformation achieved with the morphology of the joints. Experiments were conducted to characterize the effect of both joint shapes and structural materials on the motion. Results are compared with that of natural medusa gastrodermal lamella and analyzed using the theoretical model. By including the features inherently present in natural jellyfish, the propulsion efficiency was found to be increased.

7644-83, Poster Session

Characterization of tensile mechanical response of epoxy resins

M. Yekani Fard, Y. Liu, A. Chattopadhyay, Arizona State Univ. (United States)

For any mechanical simulation of composite material, properties of fiber and matrix must be known. When conducting mechanical simulation of polymer matrix composites using micro-mechanics approach, experimental tensile stress strain diagrams are needed for constitutive modeling of the resin matrix material. The mechanical response of a two phased Epon 863 (recently known as FS-A23) and hardener EPI-CURE 3290 (recently known as FS-B412) is investigated in tensile loading. The resin is tested at low strain rate of about 100 str/sec in room temperature. The tensile properties will be measured using actuator data, extensometers, and optical measurement techniques. Two kinds of dog-bone geometry with uniform and reduced thickness are used. Load deflection records measured through the loading mechanism of the testing machine are adjusted by subtracting extraneous deformations associated with the compliance of the machine. Yield tensile stress, maximum tensile strength, tensile strength at failure, modulus of elasticity, strain hardening ratio, yield tensile strain, strain at the maximum strength, strain at the failure, and toughness of the material up to specified extensions will be calculated and reported. The tensile stress strain response of the polymer will be simplified using the characteristic points.

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7644-84, Poster Session

Design of RF MEMS switches without pull-in instability

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Micro-electro-mechanical systems (MEMS) switches for radio-frequency (RF) signals have certain advantages over solid-state switches, such as lower insertion loss, higher isolation, and lower static power dissipation. Mechanical dynamics can be a determining factor for the reliability of RF MEMS. The RF MEMS ohmic switch discussed in this paper consists of a plate, suspended over an actuation pad by four double-cantilever springs. Closing the switch with a simple step actuation voltage typically causes the plate to rebound from its electrical contacts. The rebound interrupts the signal continuity and degrades the performance, reliability and durability of the switch. The switching dynamics are complicated by a nonlinear, electrostatic pull-in instability that causes high accelerations. Slow actuation and tailored voltage control signals can mitigate switch bouncing and effects of the pull-in instability; however, slow switching speed and overly-complex input signals can significantly penalize overall system-level performance. A step toward one solution is to consider a pull-in-free switch design. One goal is to determine how simple RC-circuit drive signals and particular structural properties influence the mechanical dynamics of an RF MEMS switch designed without a pull-in instability. In this investigation, we develop a validated modeling capability and subsequently study switch behavior for variable drive signals and switch design parameters.

7644-87, Poster Session

Plane stress analysis of a clamped-clamped beam with piezoelectric/piezomagnetic sensors under uniform temperature

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A finite element model involving the mechanical, electrical and magnetic fields have been used to analyze the behaviour of electric and magnetic potential of mild steel clamped - clamped beam embedded with multiphase magnetoelectroelastic or piezoelectric or magnetostrictive patches in the thermal environment. The current formulation demonstrates to predict the thermal deformation and sensor behaviour of the piezoelectric/piezomagnetic, piezoelectric and magnetostrictive patches under uniform temperature load. The uniform temperature rise 50°C is considered for the present study. A sensor patch is embedded to the base structure (mild steel) on its top surface is considered. The sensor patch is made of piezoelectric material PZT-4, magneotstrictive material Terfenol-D epoxy and multiphase magnetoelectroelastic material (BaTiO3-CoFe2O4) with different volume fraction. The behaviour of the sensor is performed for patch located at fixed end and middle of the beam due to uniform temperature rise and symmetry boundary condition about the middle of the beam. The transverse displacement, electric and magnetic potential are plotted along the length on the top surface of the sensor layer. The numerical study compares the behavior of sensor on electric and magnetic potential of the piezoelectric, magnetostric and multiphase magnetoelectroelastic sensor material. The numerical simulation shows that the electric and magnetic potential depends on the location of the sensor patch. The advantageous to place the sensor patch at the middle of the beam for clamped-clamped beam in a uniform thermal environment. The multiphase magnetoelectroelastic sensor shows the higher variation as compared to the single phase piezoelectric or magnetostricitve materials.

7644-89, Poster Session

Effect of surface modified Fe3O4 nanoparticles on rheology of bidisperse magnetorheological fluids

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We study the effects of Fe3O4 nanoparticles on bidisperse MR fluids, and determine an optimum percentage of nanoparticles to increase stability and yield stress. Fe3O4 nanoparticles were prepared via chemical co-precipitation and surface modified with a silane coupling agent. Nanoparticles were characterized via FTIR, XRD, SEM, and VSM. These results show that the nanoparticles (about 20nm diameter) were paramagnetic, with typical Fe3O4 crystal structure. These surface modified Fe3O4 nanoparticles were used as an additive to prepare a novel MR fluid in combination with carbonyl iron microparticles suspended in silicone oil. MR fluid stability and rheological properties were experimentally investigated. The results show that adding a small percentage of the surface modified Fe3O4 nanoparticles into the MR fluid results in a significant change in the sedimentation stability, off-state viscosity and yield stress of the MR fluid. A critical concentration, that is 1.5 wt%, was determined. Below this critical concentration, the sedimentation ratio decreases, and the yield stress increases as Fe3O4 nanoparticle concentration incerases. Furthermore, at this 1.5wt% nanoparticle concentration, the sedimentation ratio reaches a minimim 15% value, and yield stress increases by 26% at 0.6T, compared with the MR fluid without Fe3O4 nanoparticles. Beyond this critical value, the sedimentation ratio and the off-state viscosity increase, and the yield stress decreases. Thus, a key conclusions is that adding an appropriate concentration of surface modified Fe3O4 nanoparticles into MR fluids can improve the stability and yield stress of MR fluids.

7644-90, Poster Session

Dynamic analysis of slider crank mechanism and two-link manipulator using constraint technique

M. M. Hegaze, A. M. El-Nady, E. Morgan, Military Technical College (Egypt)

The important of the slider crank mechanism and two-link mechanism is that they are the key-player in many mechanical and structural systems. A family of joints in form of library to carry out kinematical and dynamical analyses of mechanical systems was introduced in earlier work by authors. Joint programming package was designed employing the proposed joint library. In this paper, parametric investigations have been carried out on two different types of mechanisms, closed loop mechanism (slider-crank mechanism) and open loop mechanism (two-link manipulator) to illustrate their effects on the response of the systems. The proposed applications have been described based on the type of joints and the number of degrees of freedom of the mechanism. Based on Lagrange multipliers theorem, the dynamic and inverse dynamic analyses have been carried out to calculate the reaction forces.

7644-91, Poster Session

Finite element analysis of fatigue damage of composite laminated structures under stochastic loading

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Composite materials are increasingly believed to be the materials of the future with potential for application in high performance structures. One of the reasons for that is the indication that composite materials have a rather good rating with regard to life time in fatigue. The present paper comprises theoretical and experimental research into the implementation of composite materials in structure applications. A finite element derivation was carried out based on Mindline theory. Experimental measurements were carried out with two different types of composite materials, carbon/epoxy and glass/epoxy in order to obtain fatigue life diagrams (S/N diagrams) to be used for the fatigue damage assessment. Fatigue damage assessments were developed to predict the fatigue behavior of laminated structures based on damage by initiation under random load. A computer program was built based on the proposed finite element theory to carry out the previous analyses. The validation of the developed program for some analyses such as stress analysis, natural frequency analysis and fatigue analysis was successfully achieved using a number of composite case studies. A parametric study was also carried out to illustrate the potential of the program to be used as a good optimization tool.

7644-92, Poster Session

Attenuation behavior of multimode optical fibers bended several times and comparison with current models

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The applications of optical fiber today are multiple (Telecommunications, Medical, military industry, aerospace, civil engineering). Due to their high functionality and versatility is of vital importance to study deeply the behavior of the optical signal when the fiber is subjected to bending under various curvatures. Such studies are the basis for the construction of analytical models that can predict the behavior of the attenuation of a multimode fiber when it is flexed.

This paper presents an overview of recent analytical models that have been developed for the study and simulation of light attenuation inside optical fibers. Specifically in this work those models were evaluated and compared with experimental data. This data were obtained from a complete characterization of the optical signal traveling through the optic fiber under one geometric configuration circular.

To perform this characterization was designed a closed circuit in which one end of the fiber was connected to the OTDR equipment and the other end connected to an oscilloscope. With this design we observed the behavior of transmitted light when the fiber is bent. The characterization results allow to assess the models established by various authors, evaluating the experimental data was observed that the models proposed to date not entirely correct, because they do not consider some factors that are crucial for optimal prediction of the behavior of light transmitted from an optical fiber when it is flexed. These factors will then be presented and discussed.

7644-95, Poster Session

Mechanical behavior of coupled DEAP actuator and negative-rate bias spring system

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When a high electric field is applied across a dielectric electro-active polymer, the stiffness in the in-plane direction decreases. This change in stiffness can be used to generate linear actuation in the out-of-plane direction if the DEAP is subject to a suitable bias force. This bias force is commonly provided by a linear spring, but a recent patent application by Artificial Muscle, Inc. [1] suggests the use of so-called negative-rate bias springs to increase the achievable stroke. These springs are geometrically non-linear systems with bi-stable mechanical characteristics featuring a negative stiffness between equilibrium points that can be efficiently matched to the DEAP load/deformation behavior.

This paper presents a mechanical model and experimental investigation of a commercially available DEAP coupled with such a negative-rate bias spring (NBS). A simple model is introduced to explain the non-linear snap-through behavior of the bi-stable NBS, and subsequently the coupled behavior of a parallel NBS/DEAP system is studied. The paper also presents experimental results obtained with a number of different NBS prototypes, which are used to validate the model predictions. Finally, comparisons are made with conventional spring systems to illustrate the potential for stroke increase.

7644-97, Poster Session

Influence of a non-uniform stress on the electromechanical

transduction coefficient of a magnetostrictive unimorph

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When a magnetostrictive layer is attached to a support beam, the magnetic properties of the magnetostrictive layer are sensitive to bending of this unimorph structure. The changes of the magnetic properties can be sensed by a planar coil on top of the magnetostrictive layer or a solenoid around the unimorph structure. As a utilization of this a magnetostrictive bending sensor can be build up which, besides the sensor application, is also potentially suited for energy harvesting. This paper deals with the development of an electromechanical network model for the magnetostrictive unimorph structure. Only small variations of the mechanical, magnetic and electrical quantities around an operating point can be assumed. This allows the development of an efficient linear network model of the structure. For typical applications a non-uniform stress distribution in the magnetostrictive layer results. Thus the electromechanical transduction coefficient varies over the magnetostrictive layer area. To account for the spatial varying properties, the unimorph and the coil are discretized into finite electromechanical network elements. A good approximation of the mode shape for dynamic applications up to the first bending mode can be achieved by employing about 10 finite network elements. By simplifying the finite network model an easy to use network model is obtained which enables the fast calculation of the sensor properties. The network modeling of the bending sensor by non-uniform stress is supported by FE-models. Based on the new network model magnetostrictive systems can be analyzed as well as new designs optimized efficiently.

7644-98, Poster Session

Field induced variation of Austenite and Martensite phase coexistence region in Ni55Fe20Al25 shape memory alloy

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In this paper, we report the effect of temperature and magnetic field on the resistivity and magnetoresistance in the annealed polycrystalline ferromagnetic shape memory alloy Ni55Fe20Al25. The resistivity and magnetoresistance measurement were carried out using home made resistivity setup with Oxford superconducting magnet system. Results of these measurements are presented down to 5K and up to 8 Tesla magnetic fields in various different cycles of zero field cooled and field cooled states. These results provide the evidence of martensite transformation and phase coexistence (austenite and martensite) by first order phase transition at different fields. Ni-Fe-Al ternary alloys are relatively new Ferromagnetic shape memory alloys and are promising materials as smart materials.

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7644-34, Session 7

Stability of the magnetomechanical problem in magnetic shape memory alloys

G. Chatzigeorgiou, K. Haldar, D. C. Lagoudas, Texas A&M Univ. (United States)

Considerable research effort has focused the recent years in magnetic shape memory alloys (MSMAs), due to their ability to generate large recoverable magnetic field induced strains. The coupling of the mechanical problem, with the generation of large strains, and the magnetic problem in MSMAs leads to a strong nonlinear behavior with very interesting characteristics.

In this work we use an existing thermodynamically based model for MSMAs and we study numerically a special case, in which a MSMA specimen under constant compressive stress is subjected to a magnetic field in a perpendicular direction of the applied stress. Solving the coupled magnetomechanical boundary value problem we observe that, during the reorientation process, the material presents strong non-uniformity in the distribution of the magnetic, the stress and the strain field. Localized zones of stress, strain and magnetic field concentration are observed inside the specimen. This non-uniformity affects the reorientation process, since there are areas inside the specimen with large differences in the martensitic variant volume fraction.

The explanation for this peculiar phenomenon is the loss of ellipticity of the coupled magnetomechanical problem during the martensitic reorientation. Instability analysis is performed for the coupled magnetomechanical problem, where magnetic body forces and magnetic body couples are taken into account. The analysis reveals that there are areas in the material, where the system of partial differential equations transform from elliptic to hyperbolic. We also study parametrically the non-dimensional problem and we identify the conditions under which the magnetomechanical problem presents loss of ellipticity.

7644-35, Session 7

Magneto-mechanical behavior of magnetic shape memory alloys under simultaneously variable magnetic and mechanical loading

C. Ciocanel, H. P. Feigenbaum, Northern Arizona Univ. (United States)

The macroscopic behavior of the MSMA has been investigated through experiments performed on prismatic specimens loaded with either constant transversely applied magnetic field and variable uniaxial mechanical stress or variable magnetic field and constant uniaxial mechanical stress. The former loading condition resembles the operation of the MSMA as a sensor, while the latter mimics the operation of a MSMA actuator.

Phenomenological models have been developed to capture the macroscopic behavior under these loading conditions.

No experimental or theoretical work has been done to investigate the material response under simultaneously varied magnetic and mechanical loading. For such a loading condition one would need to know when reorientation from variant 1 to variant 2 occurs and when reorientation from variant 2 to variant 1 occurs. In practice, this condition mimics a MSMA that is used as an actuator to preserve the position of a load whose intensity varies in time, or an MSMA that is used as both an actuator and a sensor, the former requires changing the magnetic field and the latter requires changing stress. From a theoretical perspective, these conditions are an important step towards a 3D model, where it will need to be determined if reorientation from variants 1 to 2, 1 to 3, 2 to 1, 2 to 3, 3 to 1, and/or 3 to 2 is occurring.

This work presents experimental and simulated results for MSMA elements loaded with simultaneously varied magnetic and mechanical loading and discusses some of the challenges associated with the true 3D modeling of the magneto-mechanical response of these materials.

7644-36, Session 7

Constitutive model prediction of magneto-mechanical coupling response of magnetic field-induced phase transformations in NiMnCoIn magnetic shape memory alloys

D. C. Lagoudas, K. Haldar, B. Basaran, I. Karaman, Texas A&M Univ. (United States)

The unique characteristic of magnetic field induced phase transformation of NiMnCoIn magnetic shape memory alloys (MSMAs) lies in the generation of large transformation strains accompanied by high actuation frequency and high actuation stress. The macroscopic functionality of MSMAs originates from the coupled evolution of highly heterogeneous magnetic and elastic domain microstructures under external magnetic, mechanical, and thermal conditions. Experiments are performed on single crystal alloys. It is observed that applied stress in combination with the applied magnetic field facilitates the release of magnetic energy of the material. This combined effect produces considerable amount of inelastic strain.

Motivated by experiments, a constitutive model is proposed to take account of magnetic field induced phase transformation from martensitic to austenitic phase. The stress favored martensitic phase is paramagnetic, while the magnetic field favored austenitic phase is ferromagnetic. The austenitic phase is triggered off when high magnetic field is applied to the initially compressed martensitic phase.

In the present work, microstructure dependence of martensitic phase transformation is taken into account by introducing internal variables into the model. Internal variables are needed to account for strong effects of domain microstructure processes on MSMA properties, for example nonlinearity, irreversibility and varying elastic and magnetic coupling. Without explicitly considering domain configuration and evolution, the microstructure dependence is approximated phenomenologically by certain evolution laws of the selected internal variables, such as the volume fraction of the martensitic phase and the rotation of the magnetization vector in the ferromagnetic austenite.

The constitutive response is derived in a consistent thermodynamic way. The relation between the strain and the magnetic constitutive response is calibrated from the experimental data. The constitutive responses of magnetization versus magnetic field and strain versus magnetic field is then predicted and compared with the experimental results. The proposed model has the ability to predict the nonlinear, hysteretic magnetic field induced strain and magnetization response.

7644-37, Session 7

Mechanisms of domain switching in ferromagnetic shape memory alloys

V. M. Stoilov, O. Rashwan, Univ. of Windsor (Canada)

A continuum thermodynamics formulation for micromagnetics coupled with mechanics is devised to model the evolution of magnetic domain and martensite twin structures in ferromagnetic shape memory alloys. The theory falls into the class of “sharp-phase-front” modeling approaches. In addition to the standard mechanical and magnetic balance laws, a continuity of the chemical potential is postulated. Nucleation of variants and propagation of twin boundaries were investigated under combined magneto-mechanical loading and compared to recent experiments. The analysis demonstrated that phase boundary motion results in significant deformation and allowed estimation of the overall deformation in a ferromagnetic shape memory material. It has been shown that the overall deformation in ferromagnetic shape memory alloys is accompanied by evolution of particular domain patterns. The choice of such configurations is dictated by the requirement that domains remain compatible during evolution, giving rise to a low-energy path for the overall switching. The construction of this pattern is achieved using multirank laminates. Finally, numerical solutions are presented to investigate the fundamental interactions between the magnetic domain wall and the martensite twin boundary in ferromagnetic shape memory alloys.

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7644-38, Session 8

Multiferroic nanofibers by electrospinning

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Multiferroic materials possess two or more types of orders simultaneously that couple the electric and magnetic fields, and composite multiferroics have been widely explored for their excellent magnetoelectric coupling. In this letter, we report a strategy to hybrid multiferroicity at nanoscale.Multiferroic CoFe2O4-Pb(Zr0.52Ti0.48)O3(CFO-PZT), NiFe2O4-Pb(Zr0.52Ti0.48)O3(NFO-PZT) and nanocrystalline BiFeO3(BFO) nanofibers are synthesized by sol-gel process and electrospinning. After being calcined, the diameters of multiferroic fibers are in the range from 100 to 300 nm. CFO-PZT and NFO-PZT composite nanofibers are obtained by calcined in air. However, pure perovskite BiFeO3 nanofibers are obtained by using Ar as protective atmosphere. The spinel structure of CFO, NFO and perovskite structure of PZT, BFO are verified by x-ray diffraction(XRD) and high resolution transmission electron microscopy(HRTEM). Energy dispersive spectroscopy(EDS) and TEM indicate that ferroelectric phase and ferromagnetic phase grains are randomly distribute in the multiferroic composite nanofibers, and with grain size around 30 nm.The multiferroicity of the composite nanofibers are confirmed by piezoresponse force microscopy(PFM) and magnetic hysteresis. The structures and properties of the composite nanofibers are also compared with single-phase PZT, CFO, and NFO nanofibers. Excellent ferroelectric and ferromagnetic properties have been observed, which could enable multiferroic devices at nanoscale. For single phase multiferroic BFO fibers, excellent piezoelectricity and clear ferroelectric domain structure of the ultrafine fibers are characterized by high voltage piezoresponse force microscopy. Enhanced weak ferromagnetism arising from the nanocrystalline structure of ultrafine fibers is also observed.

7644-39, Session 8

Static and dynamic characterization of a magnetoelectric cantilever cutting tool

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A magnetoelectric self-sensing cantilever actuator is under development for use as a surgical tool in minimally invasive surgery. The cantilever is fabricated from Galfenol and Lead Zirconia Titanate and the electrical output from piezoelectric component is used as the self-sensing signal. The self-sensing signal, the tip displacement and the force generated by the cantilever depend on the thickness ratio of the magnetostrictive and piezoelectric layers. The work presented in this paper analyzes the static and dynamic response of the magnetoelectric strip for different thickness ratios by developing a mathematical model for the system using variational principle. The static and dynamic characterization of the magnetoelectric cantilever in bending is derived from constitutive equations for the magnetoelectric material. The equivalent stiffness and mass of the magnetoelectric cantilever is derived using variational principles for calculating the tip displacement in the cantilever. The mechanical and electrical response predicted by this model is validated with experimental data for use in a feedback loop. In addition, the electrical boundary condition of the piezoelectric layer is varied to influence the actuation properties of the cantilever tool for controlled actuation. The model developed for a single cantilever is extended to a two-segment cantilever arrangement in which one of the segments behaves like a floating base permitting easy positioning of the actuator at any location for actuation. The benefits of such an arrangement and real-time control of the actuation properties of this tool is significant in minimally invasive surgery where remote actuation with a fixed support is desired.

7644-40, Session 8

Thickness ratio effects on quasistatic actuation and sensing behavior of laminate magnetoelectric cantilevers

Y. Wang, J. Atulasimha, Virginia Commonwealth Univ. (United States)

Magnetoelectric materials have been a subject of increasing research interest due to their technological applications in magnetic field sensing devices, coil-less transformers, tunable microwave and read/write devices. In all these studies, the extension configuration has been extensively studied. However, the behavior of magnetoelectric composites in cantilever mode has rarely been studied. Compare to the extension configuration, cantilever configurations offer advantages as a co-located actuators and sensors for use in micro-surgical ablation tools and cutting tools for machining. However, an important design parameter for such applications is the ratio of the magnetostrictive to piezoelectric layer.

Among the various combinations of magnetostrictive and piezoelectric materials, the Terfenol-D/PZT composites have been widely studied because of the large magnetoelectric (ME) voltage coefficient, which ranges from 1.3V/cm Oe to 4.8V/cm Oe. But, Terfenol-D/PZT composites are not suitable for the cantilever structure since Terfenol-D is brittle and has low tensile strength. Hence, iron-gallium (Galfenol) alloys with very high tensile strength of the order of 500 MPa are used instead of Terfenol-D in this research. Most prior work on modeling laminate magnetoelectric behavior focuses on linear regimes. While a non-linear magneto mechanical plate model has been developed for a laminated structure with galfenol and aluminum layer, it does not have the ability to model variation in stress at different cross-sections along the thickness and cannot be applied to magnetoelectric materials. Hence, in this work,we need to develop a modeling tool for analyzing the effect of thickness ratio in magnetoelectric cantilevers.

7644-41, Session 8

Integration of magnetoelectric laminate composites and prestress consideration

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Magnetoelectric (ME) laminate composites have attracted substantial attention due to their strong coupling produced by the product property relation between the piezoelectric and piezomagnetic phases[1, 2]. These materials have also been prposed for a variety of sensors based measurements such as high sensitive magnetometers. [3, 4] However, studies of the integration of these ME composites into structural systems has not yet been evaluated. For example, ME laminates could be used in graphite epoxy composites much the same fashion that piezoelectrics, fiber optic sensors, or magnetostrictive sensors have been proposed [5-7]. Futhermore, the influence of mecanical loads on the ME laminate composite reponse has not been evaluated. Therefore, substantial work remains in the area of evaluate ME laminate composites into a wide range of structres including aerospace composites.

Experimental results shows the electric-field-induced magnetization as a function of DC magnetic field bias Hbias and different mechanical loads. The induced magnetization is normalized to the maximum value at 0 kN load bias. In general, each curve follows the trend that an optimum DC magnetic field bias Hbias exists to maximize the CME response. However, the CME response is also dependent upon the applied mechanical load bias and the mechanical bias shifts the optimal response. For example at 0 kN, i.e. absence of load, the maximum CME response occurs at the Hbias of 4.5 Oe. As the compressive load increases, the optimum Hbias increases and the curves shifts to higher magnetic bias fields. On the other hand, for tensile loads, the optimum Hbias shifts to lower magnetic fields as compared to higher magnetic fields for compressive loading. The maximum CME response drops dramatically under tensile loads. At 6 kN mechanical load condition, the induced magnetization is almost

zero and begins to vanish. In general, these results indicate that the mechanical load bias has a significant influence on the magnetoelectric effect.

7644-42, Session 8

Monte Carlo simulation of multiferroic $BiFeO_3$

Y. Yang, L. Li, J. Li, Univ. of Washington (United States)

Magnetoelectric multiferroics such as BiFeO3 (BFO), which simultaneously possess magnetic and ferroelectric orders, are of great interest to both fundamental studies and practical applications because of the promising coupling between magnetic and electric order parameters. In this work, a lattice model of multiferroic BFO is developed. We consider a two-dimensional square lattice of three-dimensional dipoles and magnetic spins, with dipoles ferroelectrically coupled and spins antiferromagnetically coupled. Furthermore, the spins are indirectly coupled with dipoles through the ferroelastic interactions. The electric, magnetic, and elastic energies of the lattice are evaluated, and the equilibrium distribution of dipoles and spins are realized through the Monte Carlo simulation. The coupled ferroelectric and antiferromagnetic domains are observed, and the electric switching of magnetic spins are investigated.

7644-43, Session 9

Large deformation and electrochemistry of polyelectrolyte gels

W. Hong, Iowa State Univ. (United States); X. Zhao, Z. Suo, Harvard Univ. (United States)

Immersed in an ionic solution, a network of polyelectrolyte polymers imbibes the solution and swells, resulting in a polyelectrolyte gel. The swelling is reversible, and is regulated by ionic concentrations, mechanical forces, and electric potentials. This paper develops a field theory to couple large deformation and electrochemistry. A specific material model is described, including the effects of stretching the network, mixing the polymers with the solvent and ions, and polarizing the gel. We show that the notion of osmotic pressure in a gel has no experimental significance in general, but acquires a physical interpretation within the specific material model. The theory is used to analyze several phenomena: a gel swells freely in an ionic solution, a gel swells under a constraint, electric double layer at the interface between the gel and the external solution, and swelling of a gel of a small size.

7644-44, Session 9

Stimuli responsive hydrogel simulation

K. J. Suthar, Western Michigan Univ. (United States) and Argonne National Lab. (United States); M. K. Ghantasala, Western Michigan Univ. (United States); D. C. Mancini, Agonne National Lab. (United States)

This paper presents the results of simulation of the swelling of hydrogels in steady state conditions with emphasis on its response to the environmental stimuli; such as solvent pH, and external electrical potential. Our numerical model employed and our simulation methodology is described in detail. Recent technological development in the area of biomedical field requires new kind of material, which are capable of sensing chemical change in surrounding. This type of sensing is an important aspect of a material. Recent rise of new nanotechnology promises many such application Hydrogels were found to be ideal for this purpose and hence, there is growing interest in using them for this application. This necessitates a thorough understanding of its pH characteristics in general.

We have demonstrated a methodology for simulating pH sensitive characteristics of hydrogels. Though few models were developed for simulation of hydrogel characteristics, these are based on programs implemented in individual laboratories, which are difficult to access. Hence, our model is implemented using more generic finite element software COMSOL and in this process, we developed a methodology that can be used with any software having similar capabilities.

The effect of buffer solution concentration, fixed charge density, solution pH (2-12), and electric potential (0 to 2V) on the swelling or deflection characteristics are studied in separate simulations. The results are compared with other published experimental investigations and they are in agreement.

7644-45, Session 9

Fabrication and characterization of ionic polymer gel actuators

C. Jo, H. E. Naguib, Univ. of Toronto (Canada)

Poly-AMPS (PAMPS) gel is fabricated and its electroactive behavior is studied. A weakly cross-linked anionic PAMPS gel is produced by radical polymerization using 2-acrylamido-2-methylpropane sulfonic acid (AMPS) monomers, where N,N'-methlenebisacrylamide (MBAA) and -ketoglutaric acid are used as a crosslinking agent and radical initiator, respectively. The polymerization is carried out at 323 °K for at least 24 hours. Poisson's ratio, Young's modulus and the degree of swelling of gel samples are measured as physical properties. Also, swelling and deswelling experiments are conducted in a surfactant solution using n-dodecyl pyridinium chloride (C1nPyC1). The chemo-mechanical properties of PAMPS gel are studied in a cationic dilute solution of surfactant under the electric fields. First, the effect of design parameters on the bending deformation and dynamic responses is investigated. As design parameters, sample thickness, current density, ion concentration in the surfactant solution, and cross-linking degree of gel are selected in this study. And then, the correlation effect between the parameters is investigated and the optimum condition of design parameters on the actuation is analyzed based on this data. Also, for the consideration of the effect of crosslinking type on the speed of swelling deformation, copolymerization experiments are conducted at low temperature and compared with the results using radical polymerization.

7644-46, Session 9

Piezoelectric polymer foams: preparation and charging conditions as well as touch-sensor and ultrasonic transducer properties

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Cellular space-charge electrets, so-called ferroelectrets, represent a new class of piezoelectric transducer materials. Their piezoelectric activity arises from (i) optimised structural and elastic properties of the foamed polymer film and from (ii) trapping of charges with different polarity at opposite void surfaces within the foam forming electrical dipoles. A mechanical stress applied across the film thickness leads to a large film-thickness change, if the polymer film is prepared with an elastically optimised cellular structure. Thus, the size of electrical dipoles is varied, which leads to an electrical signal across the sample thickness. Such an electrostatic or condenser principle is used in different transducer devises. However, here this transducer principle is incorporated into the material itself.

Very high piezoelectric activities with piezoelectric d33 coefficients up to several hundred pC/N were found on ferroelectrets. The underlying polarization effects as well as the dependence on the elastic properties and the foam structure itself is currently a broad research field. A detailed picture of the structural, electrical, and electromechanical features of ferroelectrets was first developed on cellular polypropylene films and recently proofed by the development of cyclo-olefine, polyethylene terephthalate and polyethylene naphthalate ferroelectrets.

Here, the ferroelectret concept is discussed briefly. In detail, the dependence of piezoelectric properties on cellular morphology and thus on elastic properties, on performed charging and on usage conditions is presented for different ferroelectrets. Furthermore, possibilities to integrate ferroelectrets in touch sensors as well as in audible and ultrasonic transducers are demonstrated and the final transducer properties are discussed.

7644-47, Session 9

Characterization of healable polymers

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Materials with an internal mechanism for damage repair would be valuable in isolated environments where access is difficult or impossible. To this end, a fibrous composite structure is envisioned with a healable polymer matrix. Current work is focused on characterizing neat polymers with reformable cross-linking bonds. These bonds are thermally reversible, the result of a Diels-Alder cycloaddition between furan and maleimide monomers. Candidate polymers are examined using modulated differential scanning calorimetry (MDSC) to confirm the presence of reversible bonding. One polymer, 2MEP3FT, was expected to have these bonds, but none were observed. A second polymer, 2MEP4FS, with a modified furan monomer does exhibit reversible bonding. Further MDSC testing and dynamic mechanical thermal analyses (DMTA) are conducted to determine material properties such as glass transition temperature, Young's modulus and quality of the polymerization. Healing efficiency is established using the double cleavage drilled compression (DCDC) fracture test. A column of material with a central hole is subjected to axial compression, which drives cracks up and down the sample. Removing the load allows the crack faces to come together, a necessary condition for the reestablishment of broken bonds. This healing process is accelerated with a heat treatment. By retesting the sample, a healing efficiency of the polymer is determined. The effect of multiple fracture/healing cycles on the healing efficiency of the polymer is considered.

7644-48, Session 10

Giant piezoelectric effect in nanocomposites with aligned PZT nanowires

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The use of piezoelectric materials have become quite common in a wide range of applications, including structural health monitoring, power harvesting, and actuation. However, piezoelectric materials are often prone to breakage and are difficult to apply to curved surfaces when in the monolithic form. Many solutions produced involve 0-3 active composites which alleviate the issue with brittleness which allow the composites for application on curved surfaces but in turn significantly reduce the composites electromechanical coupling. The research presented in this paper will create a nanowire alignment technique to fabricate 0-3 active nanocomposites with aligned piezoelectric nanowires. PZT (Lead Zirconate Titanate) nanowires are used in the creation of the nanocomposites and can be synthesized with a hydrothermal method for which the time of the run and the mineralizer concentration can control the morphology of the nanowire shape. Once the nanowires are mixed with a polymer an AC electric field is used to align the nanowires in the direction of the voltage. With direct measurement of the effective electromechanical coupling through inverse piezoelectric effect using an Atomic Force Microscope (AFM), our results will experimentally demonstrate the role of nanowire alignment on achieving high electromechanical coupling in 0-3 nanocomposites. Electromechanical coupling of the active composites with less than 50% volume fraction aligned PZT inclusion could achieve as high as that of bulk piezoelectric materials. The nanocomposites developed in this paper pave the way for new and innovative applications previously unobtainable due to limited electromechanical coupling. This high electromechanical coupling and flexibility offered by the novel active composites will provide material systems with ultimate sensing, actuation, structural health monitoring and energy harvesting and storage functionalities.

7644-49, Session 10

Nonlinear actuation response in polyvinylidene fluoride (PVDF)-based nanocomposites

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Poly(vinylidene fluoride) (PVDF) is the only commercially-available piezoelectric polymer. Research on enhancing its electromechanical properties by optimizing parameters such as mechanical stretching and poling conditions is abundantly available. However, to date, this approach has led to modest improvement in performance. An alternate approach is to enhance the electromechanical properties of PVDF by adding nanoinclusions. In this study we demonstrate the creation of a non-linear electromechanical response in non-piezoelectric (unstretched and unpoled) poly(vinylidene fluoride) (PVDF). The PVDF-SWNT nanocomposites are prepared by solution casting. Following drying, curing and electrode deposition, the experimental characterization takes place by focusing on three aspects:

a) Actuation response

b) Dielectric characterization

c) Morphology characterization

The actuation response of PVDF nanocomposites to applied electric field is tested using cantilever bending and thickness actuation configurations. The resulting strains are found to have a quadratic dependence on applied electric fields, indicative of an electrostrictive response.

The dielectric and electrical characterization is carried out using a Novocontrol broadband dielectric spectrometer. The dielectric constant shows an increase from 11 for pure PVDF to 233 for PVDF-0.4%SWNT nanocomposite (measured at 1 Hz). This high dielectric constant value at low frequency indicates an enhancement in interfacial and induced polarization in PVDF due to addition of SWNTs.

The effect of SWNTs on the polar crystalline morphology of PVDF is also studied using Fourier transform infrared spectroscopy (FTIR). Finally, we also investigate the effect stretching has on the actuation response through an increase in the polar phase and a decrease in Joule heating.

7644-50, Session 10

Microwave absorbing properties of nanocomposites with surface treated ferrite nanoparticles as filler

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Analysis of microwave absorbing properties of different polymer (epoxy) based nanocomposites are presented. The ferrite nanoparticles employed as filler materials were produced by a co-precipitation method, which was adapted for production of large amount at low cost. The nanoparticles of interest for this study were cobalt ferrite nanoparticles. For better dispersion of nanoparticles in matrix the surface treatment of nanoparticles with silane compounds was performed. The influence of the treatment on mechanical and microwave absorbing properties of nanocomposites was investigated.

Magnetic core-shell cobalt ferrite-silsesquioxane-epoxy nanocomposites have been prepared with uniform nanoparticle distribution. The nanoparticles were surface-treated with methyl- (MTMS), aminopropyl- (APTMS), glycidoxypropyl- (GPTMS) trimethoxy-silane. The optimum coating process was performed in a water/methanol solution on the particles directly after their synthesis

without prior drying. The GPTMS-coatings were 30 nm thick and the nanoparticles dispersed well in epoxy without sedimentation (Figure 1). The MTMS-coated nanoparticles (3 nm coating) formed weak agglomerates in epoxy but showed no sedimentation (Figure 1). The APTMS-coated particles formed stronger agglomerates, which led to sedimentation of the particles during molding. The GPTMS-based composites showed higher fracture toughness than the MTMS-based composites. This was attributed to the presence of larger agglomerates in the latter systems and to the stronger interface between coating and epoxy in the former systems. The material properties, permittivity and permeability, of GPTMS-based composites were measured in the frequency range between 3.95 MHz and 18 GHz. The nanocomposites showed no influence of surface coating on measured permeability. The conclusion can be done that surface treatment in form of GPTMS-coating does not disturb magnetic properties but improve the mechanical properties of the nanocomposites.

7644-51, Session 10

Nano-clay/poly(vinylidene fluoride) composite films as sensor and actuator element

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Poly(vinylidene fluoride) (PVDF) is a piezoelectric polymer material. In general, it is necessary to give large extension to PVDF film when PVDF film is used as sensor or actuator element. However, we recently found that PVDF shows piezoelectricity without large extension when Nano-clays are uniformly dispersed into it.

The aim of present study is to investigate the possibilities of Nano-clay/PVDF composite films as sensor and actuator element. Firstly, Nano-clay/PVDF composite films are fabricated by solvent casting. Also, PVDF films given large extension are prepared as comparative material. Next, the electric displacement versus electric field hysteresis loop is measured for Nano-clay/PVDF composite films and PVDF films given large extension. Then, we investigate the oscillation generated from element by electric spike wave. In this time, the dispersive waves propagating in solid with broad frequency are also detected by present prepared films. Finally, we discuss the possibilities of Nano-clay/PVDF composite films as sensor and actuator element.

7644-53, Session 10

Carbon nanotubes/ short carbon fiber nanocomposites for lightning strike protection

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With the development of modern aviation industry and materials science, the structural components of aircraft platforms are being transitioned from metals to polymeric matrix composites. However, the composite material belongs to electrically insulating materials. If struck by lightning it would be damaged more easily than other structures. The matrix resin may be degraded and vaporize, and the reinforcement fibers may break. Catastrophic structural damage may occur. Current aircraft structural composites are commonly protected using approaches such as lying of metallic meshes and foils. However, these are not ideal solutions because they increase significant weight and may be difficult to repair.

In this paper, we use multi-walled carbon nanotubes(MWNTs) and short carbon fiber(SCF) as reinforcement, and epoxy resin as matrix. We prepare conductive nanocomposites for lightning protection of aircraft. MWNTs and SCF are treated via acidification and surface modification, mechanical milling, ultrasonic dispersion method. The CNTs/SCF Epoxy (EP) conductive nanocomposites are prepared by casting method. The characterizations of materials microstructure, electrical and mechanical properties are investigated by scanning electron microscope (SEM), resistance instrument, tensile test machine and indentation experiments. Results reveal that the surface treated carbon nanotubes and short carbon fiber distribute homogeneously and form three-dimensional conductive networks within the epoxy matrix. In this way, the resistance of composite materials greatly reduced significantly. The capacity of transmiting electric current is increased, and the Damage resulting from the strikes reduce. The characterization of mechanical properties also indicates that the incorporation of nano-conductive fillers also enhanced the material elastic modulus and hardness significantly.

7644-54, Session 10

Electrothermal actuation of high-performance polyimide nanocomposites

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The novel property combinations offered by polymer nanocomposites (PNC) afford unique opportunities for sensor and actuator-based devices. Carbon nanotube (CNT) additives, both below and above percolation, have been shown to reduce the electric-fields required to induce actuation by up to two-orders of magnitude in various electrostrictive and piezoelectric polymers. This behavior is commonly attributed to local electric field modification and charge accumulation within the PNC. Alternatively, low percolation threshold and tunable conductivity can also promote actuation via resistive (Joule) heating at relatively low applied fields. Infrared imaging of polyimide (CP2) nanocomposites containing single wall nanotubes (SWNTs) and carbon nanofibers (CNFs) reveals temperature increases in excess of 225 oC at fields no greater than 0.01 MV/m applied in-plane. Thus, depending on the mechanical boundary conditions employed, thermal expansion driven buckling or mechanical softening of the polymer at Tg (209 oC) can result in macroscopic strains of up to 5%. Upon removal of the field, convective cooling is estimated to occur at rates in excess of 104 oC/s, suggesting reversible strain cycling may operate at frequencies above 0.5 kHz. Consequently, under the application of an AC voltage, both the temperature and shape of the PNC oscillate in accordance with the applied frequency, with maximum strains exceeding those previously reported by over two-orders of magnitude for a given applied field.

7644-56, Session 10

Investigations of the key mechanism of carbon-nanotube actuators and their dependencies

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Carbon Nanotubes show in the presence of an electrical field and ions interesting deflection effects. Therefore CNT material has the potential for building up flexible and adaptable structures. The deflection-needed ions are provided by electrolytes, which can be liquid electrolytes.

Within this presentation we focus on the mechanical and actuator properties of different CNT based structures. On one hand the so called bucky-papers (BP) are investigated regarding the dependency of actuator performance on the alignment of the tubes (random or aligned CNT) and the materials purity. On the other hand the usage of CNT-arrays is investigated. The actuator properties are measured by an in-plain experimental set-up using liquid electrolytes. Further on solid electrolytes which are better useable for structural applications are investigated.

7644-55, Session 11

Development and control design for macro fiber composite actuators

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Conf. 7644: Behavior and Mechanics of Multifunctional Materials and Composites IV

Macro Fiber Composites (MFC) show significant durability and flexibility in addition to being lightweight and providing broadband inputs. However, they also exhibit hysteresis and constitutive nonlinearities that must be incorporated in models and control designs to achieve the full potential of the devices. They are presently being considered for a range of applications including positioning and control of membrane mirrors and configurable aerospace structures. These applications require high precision control. In this talk, we discuss a model that quantifies the hysteresis and constitutive nonlinearities and develop a nonlinear control design for the displacement. The constitutive model is constructed using the homogenized energy framework for ferroelectric hysteresis and used to develop resulting system models. The performance of the models is validated with experimental data and numerical simulations are used to illustrate abilities of the control architecture.

7644-57, Session 11

Micromechanical analysis of viscoelastic damping performance of active piezo-carbon fiber polymer composites

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Recent studies showed the active piezo-carbon fiber polymer composites may achieve significant and simultaneous improvements in sensing/actuating, stiffness, fracture toughness and vibration damping, and these characteristics can be of particular importance in various civil, mechanical and aerospace structures. This study conducts the micromechanical analysis and finite element simulation to examine the damping characteristics of active piezo-carbon fiber polymer composites under the dynamic cyclic loadings. The viscoelastic properties of polymer matrix are considered with time-dependent relaxation modulus. The active piezo-carbon fibers used in this study are adopted from a recent study (Lin and Sadano, 2008). The damping performance is compared with the active piezo-carbon fiber and regular carbon fiber polymer composites with the same fiber volume fractures. It is found that the electric-mechanical coupling behavior can absorb dynamic energy and delay structure responses with higher viscoelastic damping. The effects of aspect ratios of piezo-carbon fibers on viscoelastic damping performance are also investigated. This study showed the promise in using this type of polymer composites to improve structure dynamic stability.

7644-58, Session 11

Magnetomechanical properties of magnetostrictive composites with high volume fraction Terfenol-D powder

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The role of Smart Magnetic Materials (SMM) is still increasing. One type of SMM are Giant Magnetostrictive Materials (GMM) which can be represented by i.e. Terfenol-D. The biggest difficulty with mechanical application of GMM is its brittleness. On the other hand, increase of frequency generate meaningfully eddy currents. These disadvantages tend to search new solutions in a form of composite materials with giant magnetostriction (GMMC). The matrix for GMMC most often is an epoxy resin with magnetostrictive material inside (in a form of powder, flakes or tiny rods made of i.e. Terfenol-D). Several composites, with outstanding magnetostrictive properties, have been synthesized combining an epoxy resin with polycrystalline powders of Terfenol-D. Composites consisting particles with a different size distribution. Application of appropriate way of compression allowed to achieve composites consisting near 70% volume fraction of Terfenol-D powder in comparison with about 48% volume fraction of reinforcement in traditional production way. Composites had random and preferential orientation which was obtained by curing the material respectively with or without a magnetic field. The quasistatic magnetomechanical properties of the composites were investigated and compared with monolithic Terfenol-D alloy. The magnetostrictive response has been studied as a function of the Terfenol-D particle size distribution, and the content of magnetostrictive particles in the composite. The highest response was obtained for a composite having 70% volume fraction of particles. Investigated composite are promising magnetostrictive material enable to create a new type of actuators and magnetic field sensor.

7644-88, Session 11

Non-linearity in piezo-fiber reinforced composites: an asymptotic approach

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Development of Piezoelectric Fiber Reinforced Composites (PFRC) has enabled new applications towards electro-thermo-mechanical sensing, actuation and power harvesting. The conformability of PFRC enables them to be conveniently incorporated on or into many real-life structures whose surfaces, in general, are curved. They have a strong, voltage dependent actuation authority and can interact with dynamic systems at frequencies from about 1Hz to 1MHz. Because these piezoelectric fiber diameters are much smaller than the typical wavelengths of interest, homogenization techniques become both necessary and useful to describe the behavior.

Through this work, an asymptotically correct model will be presented for the micro-electro-mechanical analysis of PFRC, using Variational Asymptotic Method (VAM). VAM is a mathematical tool developed by Berdichevskii [1979]. This method enables solutions in closed form even to some complex problems with inherent small parameters. VAM has been employed in the current work as a tool to split the original 3D electro-mechanical problem of a representative volume element into a 1D problem tangential to the length of the piezo-fiber and a 2D cross-sectional problem. Apart from splitting the problem for dimensional reduction and computational efficiency, VAM also directly provides accurate solutions to the 2D cross-sectional problem, incorporating the influence of both the primary material constituents in an asymptotically correct fashion. Thus VAM enables one to analyze the original problem in a mathematically rigorous and yet computationally tractable manner.

The unit cell of the PFRC considered here, consists of a single piezo-fiber of circular cross-section surrounded by a piezoelectrically inactive polymer matrix. The size of the matrix sleeve is based on the volume fraction. The circular cross-section is significant because of the commercially available version of the PFRC, namely the Macro Fiber Composites (MFC) originally developed by NASA. This unit cell is treated as a slender beam. To simplify the analysis and provide certain insights, mechanical and electric effects were studied independently first, then they were rigorously coupled. Hence, this work consists of three broad sections. First section deals with the mechanical analysis of PFRC. The structure is homogenized and effective material constants are obtained. Second section deals with the electric effect of PFRC and effective dielectric coefficients are obtained. Third section deals with the fully coupled analysis of the PFRC and effective piezoelectric coefficients are obtained as a function of the piezoelectric coefficients of the constituent fiber. The analytical results obtained are then used to explore possible implications for design and analysis as well as numerical studies.

7644-59, Session 12

Mechanically-tunable composite filter at low frequencies

S. Wheeland, A. V. Amirkhizi, S. Nemat-Nasser, Univ. of California, San Diego (United States)

Previous studies into the possibility of a plasmonic medium of a coiled conductor array in air have shown promise. This work serves to evaluate the possibility of creating a mechanically-tunable composite filter at low frequencies. Copper springs of various gauges were created with varying starting pitches using a coil winder. These springs were then embedded into a flexible host polymer. The mechanical

and electromagnetic properties of each spring design were predicted and tested. Two horn antennas were used to characterize the overall electromagnetic (EM) properties of the composite. The pitch of each spring was increased mechanically through application of force to the entire polymer-metal composite at equal intervals, with an EM test completed at each step. Using an Agilent 8510C Vector Network Analyzer (VNA), the frequency spectrum within the microwave range was scanned. Relative amplitude and phase measurements were taken at equal frequency and pitch steps. With no polymer surrounding the springs, plasmon turn-on frequencies were observed to span the microwave bands as the pitch of the springs were increased. Similar results are expected with the springs embedded in a polymeric matrix. These results suggest a method of creating a mechanically-tunable composite filter for use at low frequencies.

7644-60, Session 12

Mechanically tunable plasmon frequency using a spring array

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Composites with plasma frequencies in microwave range can be used as electromagnetic filters. The permittivity of a material transitions from negative to positive at the plasma frequency. Below the plasma frequency, the material is highly reflective. Above the plasma frequency, it is transparent. There are a couple of established ways to make composites with plasma frequencies in the microwave range. One method is to embed wire coils in a material. Wire coils have four parameters that affect the plasma frequency: pitch, wire thickness, coil inner diameter, and coil spacing. Springs are a form of wire coils with a mechanically adjustable pitch. For this project, an array of non-magnetic springs was placed in a test frame. The springs alternated between left and right-handed in order to reduce system chirality. Two horn antennas, one on each side of the test frame, were used to send and receive microwave signals. The horn antennas were connected to a vector network analyzer (VNA). The VNA returns scattering parameters that were used to calculate the permittivity and permeability of the system. Between each set of measurements, the springs were uniformly extended. This increases the pitch of the springs while leaving the other spring parameters constant. For each spring extension, the permittivity adheres to the Drude-Lorentz model and is zero at the plasma frequency. Furthermore, increasing the pitch of the springs increases the plasma frequency of the material. Therefore it was experimentally determined that the material has a mechanically tunable plasma frequency.

7644-61, Session 12

Strain sensing applicability of macro fiber composites

D. M. Pisani, C. S. Lynch, S. Liu, Univ. of California, Los Angeles (United States)

Piezoelectric macro fiber composites (MFCs) have been widely used as planar-actuator devices due in part to their robust flexibility, directional actuation, and utilization of the d33 piezoelectric mode. By investigating the converse piezoelectric effect, MFCs can be used as a dual strain sensor-actuator. The current manufactured MFC yields severe hysteresis in even moderate uniform strain fields of 200 microstrains. These non-linearities prove challenging in developing a high precision strain sensor. In order to fully develop a sensor/actuator, an optimized MFC must be designed. To understand the non-linear behavior of current MFCs, a 2-d finite element code has been developed to run piezoelectric material simulations on the MFC geometry. This code contains a fully multiaxial micromechanics model based on a constitutive law and domain switching criterion. It solves the linear piezoelectric problem with incremental electric potential loading and subsequently unloading, resulting in a strain and electric field calculation of each element. From the finite element model, polarization, polarization reorientation (remnant polarization), strain, remnant strain, and stress distribution, including their component in both Cartesian and polar coordinates, have been studied in order to determine what material/geometry variables need to be addressed to optimize MFCs as strain sensors.

7644-62, Session 12

Influence of content level and particle size of nickel powders on piezoresistivity of smart cement-based composites

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The piezoresistivity of cement-based composites has attracted a lot research attention due to its potential application in structural health monitoring. In order to explore the influence of content level and particle size of nickel powders on the piezoresistivity of cement-based composites, the electrical resistivity of cement-based composites containing nickel powders with particle sizes in the range of 3-7μm, 2.6-3.3μm and 2.2-2.8μm was measured and its variation under uniaxial compression was studied. The differences in electrical conductivity and piezoresistivity of these composites were investigated by examining the morphology of composites using scanning electron microscope. The experimental results show that content level and particle size of nickel powders are two key factors that influence the piezoresistivity of cement-based composites, which are due to the different conductive characteristics in composites. It is also found that the cement-based composite containing 24 vol.% of nickel powder with particle size in the range of 3-7μm possesses moderate electrical conductivity and the best piezoresistivity among cement-based composites with different content levels and particle sizes of nickel powders.

7644-63, Session 13

Rapid nanoimprinting and piezoresponse force microscopy of ferroelectric poly(vinylidene fluoride-trifluoroethylene) copolymer films

Y. Liu, J. Li, Univ. of Washington (United States)

Patterned poly(vinylidene fluoride-trifluoroethylene) [P(VDF-TrFE)] ferroelectric films with feature size down to nanometer scales have their scientific and technological significances. In this talk, we demonstrate an enhanced rapid nanoimprinting process on P(VDF-TrFE) copolymer films with feature size down to 100nm in just 3 minutes. The structure and crystallinity of the thin film were measured by scanning electron microscope, atomic force microscope and X-ray diffraction. The ferroelectricity of the imprinted films was investigated by surface potential measurement and piezoresponse force microscopy. Electrical properties of P(VDF-TrFE) films were also studied utilizing switching spectroscopy PFM (SSPFM) mode, which allowed real-space mapping of switching behavior and electromechanical activity. The SSPFM measurements were carried out at different temperatures. The obtained piezoresponse phase hysteresis loop and amplitude butterfly loop results showed that the coercive field of the film is reduced with the increase of temperature and finally lost when the temperature approached the Curie temperature. Also, the effects of imprinting conditions have been investigated, and the optimal imprinting parameters for excellent pattern transfer have been identified. The application of the imprinted polymeric pattern as a four-state ferroelectric memory has also been demonstrated and discussed.

7644-64, Session 13

Voltage creep effect on actuation behavior of cellulose electro-active paper (EAPap)

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Andong National Univ. (Korea, Republic of)

The voltage creep behavior on actuation performance of cellulose based electro-active paper (EAPap) has been studied. Because the actuation of EAPap is originated from both the inner ionic movement in cellulose and its piezoelectric behavior, the actuation can be affected by the external field. When the external field applied, cyclic hysteresis of P-E loop is observed. In order to investigate the detail of actuation behavior of EAPap actuator, the detail actuation response - called voltage creep- is required. The voltage creep which can reduce the response and the actuating accuracy of actuator is one important issue in order to control the micro/nano scaled positioning of smart material devices. In this paper, we present the voltage creep phenomena of EAPap, which will give more detail information to understand EAPap as well as other polymer based smart materials.

7644-65, Session 13

Modeling the transduction of IPMC in 3D configurations

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The Finite Element Analyze (FEA) methods have proven to be applicable for modeling the basic transduction sheets(cantilevers) of ionic polymer-metal composite (IPMC). Simple physical models can simulate ion transport and corresponding strain. More complicated models also add the effect of the electrode, both surface and electrochemical ones.. In this work we propose a FEA model for IPMC materials of different shapes. The new model is fully three dimensional. When dealing with 3D transduction, the electrode surface geometrical properties of IPMC becomes more important as well. For instance, there are several ways how to attach the electrodes to a cylindrical IPMC to get various deformation modes. The proposed model considers the electrode placement and provides sufficiently accurate transduction estimate for more complicated IPMC structures.

7644-66, Session 13

Finite element modeling of the electromechanical coupling in ionic polymer transducers

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Several researchers are actively studying Ionomeric polymer transducers (IPT) as a large strain low voltage Electro-Active Polymer (EAP) actuator. EAPs are devices that do not contain any moving parts leading to a potential large life time. Furthermore, they are light weight and flexible. An IPT is made of an ion saturated polymer usually Nafion, sandwiched between two electrodes made of a mixture of Nafion and electrically conductive particles usually RuO2 or platinum. Nafion is an acid membrane in which the cations are mobile while the anions are covalently fixed to the polymer structure. Upon the application of an electric potential on the order of 2V at the electrodes the mobile positive ions migrate towards the cathode leading to bending strains in the order of 5%. Our earlier studies demonstrate that the cations develop thin boundary layers around the electrode. Later developments in this finite element model captured the importance of adding particles in the electrode. This study presents the electromechanical coupling in ionic polymer transducers. Since all our earlier models were restricted to the electro-chemical part, here we will introduce the chemo-mechanical coupling. This coupling is performed based on previous studies (Akle and Leo 2006) in which the authors experimentally showed that the mechanical strain in IPTs is proportional to a linear term and a quadratic term of the charge accumulated at the electrode. The values of the linear and quadratic terms are extracted from experimental data. Furthermore this finite element model captures the mechano-chemical coupling through the fact that once the material is strained the charge concentration is decreased. A comparison demonstrating the importance of adding the mechano-chemical coupling effect on the electromechanical model is presented. Finally a comparison between the numerical model and experimental data of the mechanical displacement response due to an applied electric potential is established.

7644-67, Session 13

Actuation and sensing of a dielectric EAP actuator

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Dielectric Electro-Active Polymers (DEAP's) have become attractive material for various actuation and sensing applications such as light weight and energy efficient valve and pumping systems. This paper provides a systematic experimental investigation of the quasi-static and dynamic electro-mechanical properties of a commercially available DEAP actuator. Experiments are conducted to observe the actuators performance under various spring biased and mass loaded conditions. The force and stroke capabilities are investigated while the actuator is electrically loaded with cyclic voltages from the low to high frequency regime. The sensing capabilities of the actuator are tested using a method similar to that used by Jung et al. 2008 which uses the DEAP actuator as a variable capacitor in a high pass filter circuit [1]. This sensing circuit produces a direct voltage output when the actuator is displaced. This response is studied under a variety of excitation schemes and displacement rates. The resulting behavior of the actuator is then correlated to the viscoelastic and electro-static properties observed during previously conducted electro-mechanical characterization tests. All experiments are conducted with a particular focus on the hysteretic and rate-dependent material behavior.

7644-68, Session 14

The effect of scaling on performance of elastomer composite actuators

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Reconfigurable composite and hybrid systems have the potential to enable adaptive structures and vehicles that are optimized for a given performance need. Compact actuation that is seamlessly integrated into the materials system has the potential to provide rapid reconfiguration with a fine level of displacement control without the significant weight and volume of traditional mechanized devices. This study investigates the effects of scale (diameter and length) on the performance of McKibben-like Rubber Muscle Actuators (RMA). When pressurized, the diameter of cylindrical RMAs increases and length decreases to produce axial forces over 30X greater than produced by equivalent pneumatic cylinders. A series of RMAs with nominal braid diameters of 0.05 to 0.50 inches were fabricated, with two lengths for each diameter. Actuation force results match well with predictions. Individual test results vary due to variation in activation pressures, as expected, but also vary with lengths greater than critical lengths, which was not expected. Although actuation force per unit diameter decreases as diameter decreases, actuator force per unit cross-sectional area does not vary with diameter. If one assumes that the actuators are loaded in parallel, and that each actuator has a minimum critical length, then the force per unit volume should increase as diameter decreases which would enable ready integration into an adaptive composite system. However, the increase in force per unit volume may be inversely effected by activation pressure and actuator length. More investigation into the effects of activation pressure and actuator length on actuator force per unit volume is needed.

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7644-69, Session 14

Effect of particle size and volume fraction on tensile properties of fly ash/polyurea composites

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Polyurea is the generic term for the block copolymer formed from the reaction of diisocyanates with polyamines. It has several interesting and superior mechanical properties, e.g. some polyureas are able to reach tensile strengths of 6000psi and stretch up to over 500% strain. Fly ash which is a by-product of coal burning or heavy fuel oil combustion consists of hollow particles with porous shell. Accordingly, it has been introduced into various polymers and metals to reduce cost and achieve low density or other special properties. This work develops a composite which is made of fly ash and polyurea. A one-step method was chosen to make pure polyurea and polyurea matrix for the composites based on Isonate® 2143L (diisocyanate) and Versalink® P-1000 (diamine). Various composite samples were made by changing the size of fly ash particles and volume fraction of fly ash. The tensile properties of the pure polyurea and fly ash/polyurea (FA/PU) composites were analyzed using an Instron load frame with a 1 kN Interface model 1500ASK-200 load cell. We present the results of a collection of experiments for which the volume fraction and average size of the fly ash particles were varied and the tensile stress-strain curves, tensile strength, specific tensile strength and strain at break were determined.

7644-70, Session 14

Ballistic performance of polyurea-coated armor grade ceramic tiles

A. Samiee, Univ. of California, San Diego (United States)

The use of ceramics as energy absorbents has been studied by many researchers and some improvements in the ballistic performance of ceramic tiles have been made by coating them with different classes of materials (e.g. E-glass/epoxy, carbon-fiber/epoxy, etc.). Using ceramics for energy absorbing applications leads to a significant weight reduction of the system. Therefore, any modification to the ceramic configuration in the system which leads to more energy absorption with the same or less areal density is significant. On the other hand, polyurea has been proved to be an excellent energy dissipating agent in many applications. Inspired by this, we are studying the effect of coating ceramics with polyurea and other materials, on the energy absorption and ballistic performance of the resulting ceramic-based composites.

In this study, we investigate the effect of a layer of polyurea on its ballistic efficiency. To this end, we have performed a set of penetration tests on polyurea-ceramic composites. In our experiments, a high velocity projectile is propelled to impact and perforate the ceramic-polyurea composite. The velocity and mass of the projectile are measured before and after it has pierced the sample. The change in the kinetic energy of the projectile is evaluated and compared for different polyurea-ceramic configurations (e.g., polyurea on front face, polyurea on back face, polyurea between two ceramic tiles, etc.). The experimental results suggest that polyurea is not as effective as other restraining materials such as E-glass/epoxy and carbon-fiber/epoxy.

7644-71, Session 14

Interface damage analysis of braided composites subjected to axial tensile loading

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Textile composites are being widely used in the fields of astronautics, space, marine, automotive and off-shore due to the special properties compared with traditional laminate composites, combing high stiffness and strength at low density, high tolerance, high-specific energy absorption behavior and excellent in plane shear behaviour. 3D four-step braided composites, one kind of textile composites, are manufactured by braided preforms impregnating and solidifying with resin material. The mechanical behavior of the braided composites under tensile loading is studied by experiment and computational micromechanics. The interfacial debonding between yarn and matrix which is one of main damage modes is found in experiment. Interfacial damage is considered by cohesive zone model in FEA of a representative volume cell (RVC) of the braided composites. Interfacial damage evolution law adopts energy type damage evolution in which the fracture energy is defined by the function of the mode mix using the Benzeggagh-Kenane (BK) fracture criterion. A parametrical study is evaluated the effect of interfacial properties on the stress-strain curve and corresponding failure modes. The damage development of the braided composites with interfacial damage is discussed. It is found that the interfacial damage which is one of factors to cause the nonlinear stress-strain relation can decrease the tangential modulus but not control the ultimate strength. The interfacial strength is one of main parameters to influence the interfacial damage.

7644-72, Session 14

Bending mechanical properties of metal honeycomb sandwich structure with interface connection defects

X. Kong, X. He, L. Shi, Harbin Institute of Technology (China)

Thermal protection system is one of the key technologies of reusable launch vehicle (RLV). The ARMOR TPS is one of important candidate structure of RLV. ARMOR TPS has many advantages, for example: fixing easily, longer life, good properties, short time of maintenance and service. In comparison with traditional TPS, the ARMOR TPS will be the best selection for all kinds of RLV. So the ARMOR thermal protection system will be used in aviation and spaceflight field more and more widely because of its much better performance. ARMOR TPS panel is above the whole ARMOR TPS, and the metal honeycomb sandwich structure is the surface of the ARMOR TPS panel. So the metal honeycomb sandwich structure plays an important role in the ARMOR TPS, while it bears the flight dynamic pressure and stands against the flight dynamic calefaction. Because the active environment of metal honeycomb sandwich structure is very formidable, it can produce interface connection defects which can exist in the process of manufacture as well. Bending mechanical properties of the metallic honeycomb sandwich structure with defects are analyzed to obtain damage tolerance of the structure. The effect of shape, dimension and location of defects on the bending mechanical properties is conducted by experimental study. Then finite element analysis is performed to validate the experimental results. Haynes214 which is a kind of super alloy materials with high performances is chosen as both face sheet and core in this paper.

7644-99, Session 14

Three-dimensional piezoelasticity solution for piezolaminated

angle-ply cylindrical shells featuring imperfect interfacial

bonding

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Predicting the effect of imperfect interfacial bonding in composite laminates on their response is extremely important for reliable

design of structures made of such laminates, as used in aircrafts, spacecrafts, submarines etc. The problem becomes more pertinent in smart laminated structures integrated with piezoelectric sensors and actuators, due to presence of high transverse stresses under actuated condition. The work presents an analytical three-dimensional solution for simply supported angle-ply piezoelectric (hybrid) laminated cylindrical shells in cylindrical bending with interlaminar bonding imperfections, in an electro-thermo-mechanical loading environment. The bonding imperfection is modeled by considering the jump in the displacements, electric potential and temperature across the non-rigid interface proportional, respectively, to the associated tractions, transverse electric displacement and heat flux. The solution includes the case when electric potentials are prescribed at the interfaces for effective actuation. A mixed formulation of governing equations is developed in terms of eight primary variables. The variables for each layer are expanded in Fourier series in circumferential coordinate to satisfy the boundary conditions at the simply supported ends. The governing equations get reduced to ordinary differential equations in thickness coordinate with variable coefficients and these are solved by the modified Frobenius method. Numerical results are presented for hybrid composite and sandwich plates with varying imperfection compli- ance. The effects of panel thickness and location of imperfect interface on the response is studied for cross-ply panels while the effect of ply-angle on the sensitivity towards imperfection is studied for angle-ply panels. The effect of weak bonding at elastic-piezoelectric interface on the actuation authority of the piezoelectric layer is also investigated. The presented results would also help assessing 2D shell theories that incorporate interlaminar bonding imperfections.

Conf. 7645: Industrial and Commercial Applications of Smart Structures Technologies IV

Monday-Tuesday 8-9 March 2010

Part of Proceedings of SPIE Vol. 7645 Industrial and Commercial Applications of Smart Structures Technologies 2010

7645-01, Session 1

Development and commercialization strategy for piezoelectric energy-harvesting power sources for gun-fired munitions

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A novel class of piezoelectric-based energy-harvesting power sources has been developed for gun-fired munitions and similar high-G applications. The power sources are designed to harvest energy primarily from the firing acceleration, but from in-flight vibratory motions as well. During the firing, a spring-mass element reacts to the axial acceleration, deforming and storing mechanical potential energy. After the projectile has exited the muzzle, the spring-mass element is free to vibrate, and the energy of the vibration is harvested using piezoelectric materials.

These piezoelectric-based devices have been shown to produce enough electrical energy for many applications such as fuzing, and are able to eliminate the need for chemical batteries in many applications. When employed in fuzing applications, the developed power sources have the added advantage of providing augmented safety, since the fuzing electronics are powered only after the projectile has exited the muzzle and traveled a safe distance from the weapon platform.

An overview of the development of these novel power sources is provided, especially designing and packaging for the high-G environment. Extensive laboratory and field testing has been performed on various prototypes; the methods and results of these experiments are presented. In addition to presenting the development and validation of this technology, methods for integrating the generators into different classes of projectiles are discussed along with strategies for manufacturing and a side-by-side comparison with competing technologies. This technology is currently at DoD Technology Readiness Level 7, and strategies for elevating through the final two levels and transitioning to commercialization are discussed.

7645-02, Session 1

Multi-source energy harvester to power sensing hardware on rotating structures

A. D. Schlichting, S. A. Ouellette, C. Carlson, K. M. Farinholt, G. Park, C. R. Farrar, Los Alamos National Lab. (United States)

The U.S. Department of Energy (DOE) proposes to meet 20% of the nation's energy needs through wind power by the year 2030. To accomplish this goal, the industry will need to produce larger (>100m diameter) turbines to increase efficiency and maximize energy production. It will be imperative to instrument the large composite structures with onboard sensing to provide structural and structural health monitoring capabilities to understand the global response and integrity of these systems as they age. A critical component in the deployment of such a system will be a robust power source that can operate for the lifespan of the wind turbine. In this paper we consider the use of discrete, localized power sources that derive energy from the ambient (solar, thermal) or operational (kinetic) environment. This approach will rely on a multi-source configuration that scavenges energy from three different energy harvesting technologies: photovoltaic, thermoelectric, and piezoelectric. Each harvester is first characterized individually in the laboratory, then they are combined through a multi-source power conditioner that combines the output of each harvester in series to power a small wireless sensor node that has active-sensing capabilities. The advantages/disadvantages of each approach are discussed, along with the proposed design for a field ready energy harvester that will be deployed on a small-scale 19.8m diameter wind turbine.

7645-03, Session 1

A mechanical battery for powering wireless sensor nodes in harsh environments energy harvesting session

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In the future nuclear waste may be stored in sealed underground repositories. The ability to provide a means of monitoring the environment of the sealed repository after a period of several decades would be beneficial. An array of Wireless Sensor Nodes (WSNs) is proposed for this purpose. To power these devices an alternative energy source, other than chemical batteries, is required. Batteries are unsuitable as their capacities will deteriorate over long periods, due to self-discharge, and may be prone to the harsh nuclear environment.

This paper explores the potential of using a 'mechanical battery', as an alternative source of energy, because these will not degrade over time. The 'mechanical battery' comprises a compressed magnetic spring and associated conversion electronics. The system consists of three annular magnets, longitudinally arranged along a shaft, with opposing magnetisation directions. This topology is proposed due to a low number of parts and can provide sufficient energy to the WSN. The central magnet is allowed to move between the two outer magnets, which are fixed to a frame. In a 'charged' state the central magnet is held against one of the outer magnets, storing energy as work has been done against the resultant force to hold the magnet in place. On release the central magnet moves through a coil, co-axially placed with the magnets, with a decaying oscillatory motion. As a result, the stored energy is partially dissipated into electrical energy if a load is attached.

In order to supply energy to a WSN the induced voltage needs to be rectified and stored intermediately in a capacitor, and then supplied to the WSN via conditioning electronics. It will be shown in the final paper that there is an optimal capacitance for which maximum energy is stored for a demonstrated configuration. The stored energy is sufficient to supply a WSN, including overcoming initial start up costs and conversion losses, for approximately seventy 'acquire and transmit' cycles. This is possible as the energy cost of an 'acquire and transmit' cycle is of the order of 0.5mJ and the stored electrical energy is approximately 200mJ, extracted from a stored energy of 2J.

The final paper will detail the development of a design tool for such systems. The tool comprises theoretical models of parameters such as the mechanically stored energy, the electromagnetic coupling coefficient and rules for the optimal initial conditions for maximum energy transfer from the mechanical to electrical domain. These are verified using measurements from the prototype.

7645-04, Session 1

Wireless energy transmission to supplement energy harvesters in sensor network applications

K. M. Farinholt, G. Park, C. R. Farrar, Los Alamos National Lab. (United States)

In this paper we present a method for coupling wireless energy transmission with traditional energy harvesting techniques to power structural health monitoring based sensor nodes. The goal of this study is to develop a system that can be permanently embedded within civil structures without the need for on-board power sources. Wireless energy transmission is included to supplement energy harvesting techniques that rely on ambient, or environmental, energy sources. This approach combines several transducer types that harvest ambient energy with wireless transmission sources, providing a robust solution that does not rely on a single energy source. Experimental

results from laboratory and field experiments are presented to address duty cycle limitations of conventional energy harvesting techniques, and the advantages gained by incorporating a wireless energy transmission subsystem. Methods of increasing the efficiency, energy storage medium, target applications and the integrated use of energy harvesting sources with wireless energy transmission will be discussed.

7645-05, Session 2

Next generation control system for reflexive aerostructures (SMP session)

M. Maddux, Cornerstone Research Group, Inc. (United States)

Cornerstone Research Group Inc. (CRG) has developed a composite structural solution called reflexive composites for aerospace applications featuring CRG's healable shape memory polymer (SMP) matrix. An integrated structural health monitoring (SHM) system autonomously monitors structural health of composite aerospace structures, while integrated intelligent controls monitor data from the SHM system to characterize damage and initiate prioritized healing through discrete heat application. Healing occurs through the reptation process and the damaged region returns to near net original shape through shape memory effect.

Compression After Impact (CAI) testing was conducted on composite reinforced shape memory polymer samples to investigate the effectiveness of healing mechanisms on mechanical performance and the ability of SHM system to characterize damage were examined. Impacted samples were compression tested before and after healing cycles to assess compressive strength of healable composite samples. SHM scans throughout test cycles were used to characterize material damage. Restoration of mechanical performance was demonstrated through healing, while SHM data showed location and extent of damage and mitigation of damage post-healing.

Intelligent controls software was refined to assess damage intensity through analysis of SHM and test data, facilitating the prognostic health monitoring capabilities of the reflexive system. Data output from the intelligent controls will serve as input to Integrated Vehicle Health Management (IVHM) systems, with potential application to Integrated Resilient Aircraft Controls (IRAC).

Reflexive composite technology has the ability to reduce maintenance required on composite structures through healing, offering potential to significantly extend service life of aerospace vehicles and reduce operating and lifecycle costs.

7645-06, Session 2

Analysis of a large-deformation shape memory polymer locking link

W. W. Clark, J. C. Brigham, C. Mo, Univ. of Pittsburgh (United States); S. Joshi, NextGen Aeronautics, Inc. (United States)

In recent years, there has been a great deal of interest in "morphing" structures, that can exhibit drastic changes in their shapes and then hold those shapes to perform specific functions. The design of these structures is complicated by the fact that during a typical morphing maneuver, the deformations and stresses can become much larger than a typical structure would experience during a deformation in its elastic range. In addition, the advent of new materials, such as shape memory polymers (SMP) enable a structural element to effectively exhibit two different elastic moduli, a stiff modulus that enables the structure to retain its shape before and after a morph, and a soft modulus that enables the morph to occur. Finally, the stimulus that enables the modulus change can also affect the structural element, its surrounding materials, and the time required to undergo a morph. For example, conventional SMP is heat-activated, so the application of high heat can complicate the stress field and even damage the material. This paper illustrates some of the design challenges of a morphing structure by presenting a finite strain, large deformation computational analysis of a composite SMP link. The link is made up of shape memory polymer (the softening material) and a backbone of shape memory alloy, which allows large deformations but ensures that the nominal shape is recovered upon return deformation. The link has been used as a locking/unlocking element in a larger morphing aircraft structure. The paper will present the details of the link itself and its functional requirements, and then will present a finite element analysis of the link, comparing the numerical load and deformation results to the experimental behavior. Features of the modeling process that will facilitate future designs will be highlighted.

7645-07, Session 2

Fabrication and testing of a shape memory polymer active rigidity 'smart joint' for wing morphing on a bat-inspired MAV

F. Geeng, J. E. Manzo, E. Garcia, Cornell Univ. (United States)

While many SMA wire actuators exist for spacecraft and robotics applications, few currently exist for micro-aerial vehicles (MAV). Cornell University's LIMS Laboratory seeks to integrate its active rigidity SMA 'smart joint' in a biologically inspired bat wing MAV to explore flight characteristics of different morphed wing camber configurations.

The smart joint is composed of a matrix of shape memory polymer with embedded shape memory alloy for strain actuation. Through selective ohmic heating via pulse-width modulated (PWM) signal, the required temperature profile is achieved to simultaneously allow polymer compliance and SMA actuation, thereby inducing joint bending. Feedback using strain gauges and thermocouples allows the joint to achieve a range of actuation to allow for multiple wing configurations.

Design and fabrication details for the joint and control system is shown. Finite element and experimental test results are compared to those from an analytical model, which is also used to predict and optimize joint behavior. Computational fluid dynamics analysis and wind tunnel test results for different morphed camber configurations are presented, showing delayed stall and increased lift. A concept membranous bat wing vehicle is presented, with test flight data as available.

7645-08, Session 2

Shape memory polymer (SMP) venting mechanism for munitions

M. J. Fisher, Cornerstone Research Group, Inc. (United States)

Cornerstone Research Group (CRG) is developing temperature-activated pressure venting mechanisms using shape memory polymer (SMP) to meet insensitive munitions (IM) requirements for solid rocket motors and other munitions. SMPs are polymers whose qualities have been altered to give them dynamic shape "memory" properties. Under thermal stimuli, SMP can exhibit a radical change from a rigid thermoset to a highly flexible, elastic material. SMP-based pressure venting mechanisms, coupled with conventional impact-resistant containers or composite cases, will offer low-cost, failsafe mitigation of violent responses to thermal stimuli, as part of a systems approach to meeting IM requirements.

CRG demonstrated the feasibility of an SMP-actuated venting system designed to relieve confinement in a solid rocket motor subjected to a slow cookoff environment. In CRG's venting design, an SMP composite provides the triggering mechanism for releasing confinement at a specified temperature. CRG constructed a prototype venting mechanism based on an internal retaining ring design and successfully tested it in a lab-scale thermal environment, and in full-scale slow cookoff testing in an analog solid rocket motor.

7645-09, Session 2

Reflexive marine systems for autonomous structural repair

M. Maddux, Cornerstone Research Group, Inc. (United States)

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Cornerstone Research Group Inc. (CRG) has developed a composite structural solution for application in marine environments featuring CRG's healable shape memory polymer (SMP) matrix. Healable matrix restores mechanical performance in the composite post-failure. Reflexive composite features the integration of three emerging technologies: marine compatible healable polymer composites, structural health monitoring (SHM), and intelligent controls.

An integrated SHM system autonomously monitors structural health of the marine vehicle. Integrated intelligent controls monitor data output from the SHM system to determine if detected anomaly is damage and initiates a targeted healing cycle through discrete heat application to the damaged area. The healing process returns the damaged region to near net original shape by shape memory effect and matrix healing.

Adapting reflexive composite solution to marine environments involved development of a marine-compatible resin and optimization of signal parameters for SHM functionality underwater. CRG's healable resin was tested and evaluated for fresh and salt water resistance. Its healing capabilities were studied after exposure. Parallel testing was conducted using two industry standard marine compatible resins. CRG's healable SMP was able to regain between 50-100% of its K1C fracture toughness post failure after healing of completely failed water soaked neat samples.

By healing damage and micro-cracks, this technology significantly reduces maintenance required on composite structures, offering the potential to significantly extend the service life of marine vehicles and reduce operating and lifecycle costs.

7645-10, Session 3

Shape memory polymer activated by microwave

Y. Zhang, F. Zhang, Z. Xu, Nanjing Univ. of Science & Technology (China)

Shape memory polymers (SMPs) with the characteristics such as large recoverability, easy shaping procedure, low density and cost, easy control of recovery temperature and so on which have motivated a flurry of interest to exploit their applications . In these SMP based devices or structure, such as medical devices and deployable structures. One of the key challenges is how to activate them reliably. In this paper a novel SMP composite material mixed with Tetra-needle zinc oxide whisker (T-ZnOw) particles were invented and this SMP/T-ZnOw composite materials owned the ability to absorb microwave and to transfer the microwave energy to heat efficiently while keeping the basic characters of SMP material. Tensile tests and cyclic thermo-mechanical experiments were performed on the SMP/T-ZnOw with different particles weight fraction to assess the impact of the T-ZnOw particles on the mechanical and memory properties of the samples. The heating efficient of the composite by low power microwave was tested with the different T-ZnOw particles ratio and it was found that the temperature in the samples increased rapidly with the T-ZnOw ratio for a fixed exposure time. Finally a prototype of a SMP device was deployed under the microwave exposure to demonstrate the feasibility of SMP actuation by microwave.

7645-13, Session 3

Shape memory polymer environmental exposure sensors

M. D. Rauscher, E. Havens, T. E. Havens, Cornerstone Research Group, Inc. (United States); J. McFerran, Naval Surface Warfare Ctr. Dahlgren Div. (United States)

Cornerstone Research Group Inc. (CRG) has developed environmental exposure tracking (EET) sensors using shape memory polymers (SMPs) to monitor the degradation of perishable items, such as munitions, medicines, or foods, by measuring the cumulative exposure to temperature and moisture. SMPs are polymers whose qualities have been altered to give them dynamic shape "memory" properties. Under thermal or moisture stimuli, the SMP exhibits a radical change from a rigid thermoset to a highly flexible, elastomeric state. The dynamic response of the SMP can be tailored to match the degradation profile of the perishable item. SMP-based EET sensors require no digital memory or internal power supply and provide the capability of inexpensive, long-term lifecycle monitoring of thermal and moisture exposure over time.

This technology was developed through Phase I and Phase II SBIR efforts with the Navy. Here, CRG presents progress in commercialization efforts to scale-up production. Fabrication scale-up, process refinements, and quality control efforts will be discussed with an emphasis on transitioning SMP materials from lab-scale development to a production environment.

7645-14, Session 3

The characterization of a deployable sandwich beam with shape memory polymer foam core

Z. Xu, Nanjing Univ. of Science & Technology (China)

The characterization of a self deployable sandwich beam with a new kind of shape memory polymer composite foam core (SMCF) was studied. In SMCF the shape memory epoxy was used as the matrix, the hollow microsphere and the chopped carbon fiber were used as the filler and strengthen material. During the material fabricate procedure, a small amount of aluminum powder and NaOH solution were added to the mixture as the foaming agent. A set of tensile tests, compress tests ,impact tests and thermal-mechanic tests were preformed on SMCF to determine the strength, failure strain, glass transition temperature, shape fixity and shape recovery properties at different temperature. The obtained shape memory foam owned the fiber reinforced cellular microstructure, with ultra-light mass, higher bulk strength and ductility and more than 500% compression/deployment ratio while keeping the basic shape memory behavior. The recovery strain was almost 100% at the 500% compression ratio after several cycles of training and the strength degration was negligible after multiple compression-deployment cycles. Long carbon fiber reniforced composite sheets were glued to the upper and lower surface of SMCF core completely as the skin of the sandwich structure. Packing/deploying test, three point bending test at packed and deployed state were performed on sandwich beams to verify the feasibility, reliability of the deployment, the stiffness and the strength of the beam. From the researching results it can be indicated that the deployable beam described in this paper has a significant potential in space applications.

7645-15, Session 3

Characteristics of shape memory polymer foams filled with hollow microsphere

F. Zhang, Y. Zhang, Z. Xu, Nanjing Univ. of Science & Technology (China)

(SMP SESSION)

Shape memory polymers (SMPs) are fairly recently developed functional polymers that find applications in many aspects, such as medical treatment, mechanism, aerospace and so on, due to the advantage of high shape recovery, good machining function and low cost etc. As a new class of shape memory polymers, shape memory polymer foams (SMPFs) have great potentials in some special areas because of the smaller density, high compress/deployment ratio as well as the shape memory properties.

In this paper, a new kind of epoxy based SMP foam composite (ESMPF) was developed. The hollow microsphere was applied as the filler and strength composite material in SMPF and a small amount of aluminum powder and NaOH solution were added to the epoxy/microsphere mixture as the foam starting agency during the manufacture process. The tensile test, compress test and thermal-mechanic cyclic test were performed to determine the strength,

shape memory properties, ultra-compress ratio and deploy ability of the SMPF. Comparing with the pure epoxy based SMP, the density of SMPF composite was decreased and the strength and ductility increased greatly. The ultra-compress ratio could be 400% at the temperature above Tg and the shape recovery ratio was almost 100%. The experiment results indicated that the obtained ESMPF have significant potential applications in self-deployable structures.

7645-16, Session 3

Deployment dynamics of fiber-reinforced shape-memory polymer structure

X. Lan, Y. Liu, J. Leng, Harbin Institute of Technology (China)

A fiber reinforced thermosetting styrene-based shape-memory polymer composite (SMPC) is developed, and then a deployable hinge is designed and fabricated using the SMPC. The main objective is to systematically analysis the deployment dynamics of SMPC hinge. Firstly, the theory of deployment dynamics of SMPC shell is presented. Then, the shape recovery performance is investigated by finite element analysis (FEA), such as deployment moment vs. angle, stress distributions, etc. The deployment process of curved SMPC shell is simulated by the geometrically nonlinear analysis. During the analytical research, the relationship of deployment moment and angle is derived by using dynamic theory. In addition, during the macroscopic shape recovery process, the shape recovery performance of SMPC is decided not only by the shape memory effect of SMP but also by the microstructural deformation mechanism of fiber and SMP. Hence, the microstructural deformation mechanisms of SMPC is investigated by using SEM. Results show that the fiber microbuckling is needed to achieve high package strain and avoid fiber failure. With the microbuckling, SMPC materials are suitable for use in deployable space structure components because of their high strain-to-failure capability.

7645-17, Session 4

Magnetostrictive actuator with hydraulic stroke amplification for active powertrain mounts

S. Chakrabarti, M. J. Dapino, The Ohio State Univ. (United States)

A hydraulically amplified Terfenol-D actuator is developed to be used as an actuator in active engine mounts. A measure of the actuator's performance is obtained through electromechanical tests in the mechanically-blocked and mechanically-free conditions. In order to better understand how the actuator compares with current technology, benchmark tests are performed on a commercial electrodynamic actuator presently being used in active mounts. The magnetostrictive actuator gives a higher frequency bandwidth of operation with lower electrical power consumption. A dynamic model is developed for the actuator. Eddy current losses are modeled as a one-dimensional magnetic diffusion problem in cylindrical coordinates. The Jiles-Atherton model is used to describe the magnetization state of the material as a function of applied magnetic fields. Magnetostriction, which is modeled as a single-valued function of magnetization, provides an input to the mechanical model describing the system vibrations. Friction at the elastomeric seals is modeled using the LuGre friction model for lubricated contacts. The model results provide accurate frequency and time domain fits to the experimental data. A major drawback of the driver material (Terfenol-D) is that it is brittle and would need to be packaged extremely carefully to ensure it remains intact inside the vehicle. An alternative solution to that could be to replace Terfenol-D with Galfenol (an alloy of Iron and Gallium) which is machinable and much more robust. A similar actuator would be built based on Galfenol and the performance of the two devices will be compared.

7645-20, Session 4

Active material based active sealing technology, part 1: active seal requirements vs. active material actuator properties

A. L. Browne, General Motors Corp. (United States); C. P. Henry, W. B. Carter, G. Herrera, G. P. McKnight, HRL Labs., LLC (United States); N. L. Johnson, I. Bazzi, General Motors Corp. (United States)

Current seals used for vehicle closures/swing panels are essentially flexible, frequently hollow structures whose designs are constrained by numerous requirements, many of them competing, including door closing effort (both air bind and seal compression), sound isolation, prevention of water leaks, and accommodation of variations in vehicle build. This paper documents a collaborative research study/exploration of the feasibility of and approaches for using active materials with shape and stiffness changing attributes to produce active seals, those whose geometry and stiffness could be changed on demand, i.e. seals with improved performance. Included as a major focus was the assessment of polymeric active materials because of their potential ease of integration into the current seal manufacturing process. Potential materials were evaluated in terms of their cost, activation mechanisms, and mechanical and actuation properties. Based on these properties, simple designs were proposed and utilized to help determine which materials are best suited for active seals. In terms of study findings, the only concepts that were judged feasible (though not yet practical) with current technology were those utilizing respectively SMA's (shape memory alloys) and EAP's, (electroactive polymers). However, even with these, considerable engineering development was felt to be required to fabricate, produce, and manufacture these concepts in a robust manner and to be able to provide the tunable range of responses desired in cost and performance competitive designs.

Paper submitted for consideration for the Smart Materials and Devices for Vehicle Applications Workshop

7645-21, Session 5

Smart material database compilation and material selection tool development

J. Park, G. N. Washington, The Ohio State Univ. (United States)

(SMART VEHICLES WORKSHOP)

In this paper, information on the various aspects of smart materials is compiled in an easy-to-consult format by conducting extensive survey of published articles and including the properties of the materials. Although many different types of smart materials are being widely used in various engineering applications, it is hard to find good documentation on the various aspects of smart materials. The compilation of a comprehensive database on smart materials enables to expedite a material selection process in the design of smart material devices or systems. Using this, industrial application designs with the materials can be improved in a time-efficient and cost-effective way. We show the compiled database in a legible format such as GUI based computer software that determines and simulates what material to use based on properties and performance. The types of smart materials include piezoelectric (polymer/ceramic) materials, dielectric elastomer, shape memory alloys, electro-rheological and magneto-rheological fluids, and thermoelectric materials. According to their functionalities, they are categorized into four groups: actuator, sensor, energy generator, and passive structural materials. The various properties of the materials in each group are characterized and compiled in a database. Currently available mathematical models and potential applications are identified to select the best model for a given purpose. In addition, we have developed a simple but effective model in case of no suitable model is determined. Finally, the current and potential applications of the materials are addressed and the associated system-level models for selected materials are developed to show the performance of the overall system.

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7645-22, Session 5

Numerical simulation of the activation behavior of thermal shape memory alloys

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Problems in using SMA in industrial applications are often caused by the simply fragmentary knowledge about the complex activation behavior. To solve this problem, Fraunhofer IWU developed a Matlab-based simulation tool to emulate the properties of an SMA wire. The tool is based on the energy balance. The contained terms result of the characteristic material behavior combined with the thermal, electrical and mechanical conditions. The model validation is realized by a labarotary experiment where the SMA-actuator elevates a constant mass. It is shown that there is almost no difference between the measured and the simulated movement of the actuator. Due to the good compliance of model and reality, it is possible to use it in a control loop. Therefore the model is implemented in a microcontroller-based rapid-prototyping-system. With the knowledge of the actual current and the measured voltage the electrical resistance of the SMA-actuator can be computed. Thereby the correlation between the resistance and the displacement of the wire is used. The transfer of the results into an industrial application is exemplified by the integration of an actuator in a throttle flap used in air condition systems of cars. The SMA-based drive will be compared to an electric drive regarding performance, control quality, weight and dimensions.

7645-23, Session 5

Modeling and validation of shape memory alloy actuated toothed linear ratchet drive (TOTLRAD) architecture

B. M. Barnes, D. E. Brei, J. E. Luntz, Univ. of Michigan (United States)

There are many linear actuator applications that require significant expandability relative to an initial compact package size while maintaining a zero power hold. These range from extreme load applications in the kilonewton range for automotive applications (e.g. hood lifting devices) to gram loading in medical applications (e.g. implantable actuators). These applications tend to impose other limiting constraints (environmental, biocompatibility, robustness, etc) and severe packaging restrictions making conventional actuation technologies like pneumatics, hydraulics, and electromechanical drives non-viable. While smart material actuators theoretically have the required energy density, current direct actuation architectures do not provide the performance and packaging form factor to meet the constraints. This paper presents a generic Toothed Linear Ratcheting Drive (TOTLRAD) architecture utilizing shape memory alloys that provides zero power hold and large displacements by accumulating repeated actuations of shape memory alloy wires. Ratcheting leverages compact packaging with high expandability while maintaining the high energy density, and high force capacity of the material at various size scales. The basic performance models are derived using a state machine kinematic model of the ratchet architecture combined with a Simulink implementation of a thermodynamic shape memory alloy material model which is validated using a planar experimental setup. The modeling foundation presented here enables optimum design of linear ratcheting actuator systems for high stroke, compact actuators ranging in force requirements across fields as diverse as medical and automotive.

7645-24, Session 5

A compact quick-release mechanism for rapid reset of SMA actuated systems

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Resistively heated SMA actuators have been demonstrated for applications that require very fast actuation. However, SMA actuators have hitherto been at a disadvantage in applications that require rapid reset in addition to rapid actuation. This is because the reset time for an SMA actuator, which is determined by the time required to cool the actuator below its Mf temperature, tends to be high when the heat loss rate from the SMA elements is low. We present a compact quick release mechanism that provides a rapid reset capability to the system by effectively decoupling the SMA actuator from the rest of the system during the actuator cool down period using an auxiliary SMA actuator. After the decoupling, the SMA actuator cools down at a rate dictated by the local heat transfer conditions while the remainder of the system (esp. the output load) resets at a rate dictated by its own dynamics. Subject to proper sizing of the two actuators, the output load can experience a reset time that is comparable to its actuation time. The system as a whole resets when both SMA actuators have cooled to a temperature below Mf. While this system can be adapted for different kinds of output loads (e.g. constant, linear spring, etc), it is especially useful for constant output loads, as in this case the auxiliary SMA actuator needs to supply only a fraction of the work output of the main SMA actuator. This leads to a compact and low cost system.

7645-25, Session 6

Ultrasonic-assisted microforming using Terfenol-D

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Ultrasonic vibration has long been used in forming processes to reduce the force required for forming, due to a measured “ultrasonic softening,” where all ultrasonic energy is concentrated along dislocations, causing further dislocations and an overall reduction in yield stress. There are also measured reductions in friction, which result in improved surface finish and tolerance. These benefits are especially useful in microforming processes, where material size effects begin to dominate. When the cross-section of the work piece becomes only a few grains thick or less, there are marked increases in both yield stress and friction, as well as reduced repeatability as grains are no longer allowed to deform in their preferential directions.

Most ultrasonic-assisted forming processes use piezoelectric transducers, whereas this study will explore the possible advantages of using Terfenol-D to provide both ultrasonic vibration and bulk forming motion. The goal is to develop a solid-state forming device, which should eliminate backlash from the system, potentially further improving geometric tolerancing. The device will include an ultrasonic stage, which consists of a simple Terfenol-D rod and coil, as well as a bulk motion stage, which will involve some sort of mechanical strain amplifier; possibly a lever type system. Terfenol-D should also provide an advantage over piezoelectric transducers in that it is strong enough to handle the force required for forming directly, simplifying system design. Furthermore, its frequency response band is much wider than that of a piezoelectric transducer, allowing less stringent frequency response requirements for the die, which could allow simpler and cheaper die design.

7645-26, Session 6

Active metal matrix composites with embedded smart materials by ultrasonic additive manufacturing

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(Smart Vehicle Workshop) This paper deals with the development of active metal-matrix composites manufactured by Ultrasonic Additive Manufacturing (UAM), an emerging manufacturing process that allows the embedding of materials into metals through ultrasonic consolidation. In the UAM process, successive layers of metal tapes are ultrasonically bonded together to form a metal matrix composite.

Current methods of creating these composites involve sintering and forging which generally require temperatures up to 565°C. In comparison, composites created through UAM typically experience a maximum process temperature of 150°C while some have been constructed at temperatures as low as 65°C. Being a low-temperature process, UAM offers unprecedented opportunities to create parts both with embedded materials (e.g., metals, fiber optics, printed circuits, polymers, smart materials, etc.) and arbitrarily shaped internal features (e.g., internal cooling channels, designed anisotropies, etc.).

UAM operates on the principle of Ultrasonic Metal Welding (UMW). In UMW, ultrasonic vibrations created by a piezoelectric transducer are transferred to clamped work pieces by a transversely vibrating sonotrode. The vibrating sonotrode imparts a static pressure and transverse ultrasonic motion to the top piece that creates a relative, friction-like action at the interface of the two work pieces. The relative interface motion causes shear deformations of contacting surface asperities, dispersing interface oxides and bringing clean metal-to-metal contact and metallic bonding between the surfaces.

In this research, UAM is used to construct an apparently solid metal block with embedded smart materials. The embedded smart materials will allow for the composite to have sensing and actuation properties. This research focuses on the creation of active metal matrix composites by embedding NiTi and Galfenol into aluminum matrices.

Our work shows UAM's ability to embed relatively large diameter shape memory NiTi wires within an Al 3003-H18 matrix. These samples were constructed by placing NiTi wires at the interface of two Al 3003-H18 tapes and then ultrasonically welding the tapes together. When embedding NiTi wires with diameters ranging from 0.001" to 0.015" the energy from the ultrasonic vibrations causes plastic flow of the aluminum tapes around the wires completely enveloping them in the matrix. Galfenol embedding trials have attempted to make magnetostrictive UAM composites by placing a 0.015" thick strip of Galfenol between two Al 3003-H18 tapes.

The Al-NiTi composites have the ability to change stiffness and are expected to exhibit sensing abilities and geometric stability over extended temperatures ranges in contrast to passive structures made from aluminum. The large difference in elastic modulus, over 100%, between the low temperature martensite phase and the high temperature austenite phase provides a mechanism for actively changing the stiffness of the composite through thermal activation. The large stiffness change can be applied in tunable vibration absorbers or for actively changing the path mobility in structure-borne noise with the goal of minimizing noise propagation. The sensing capabilities of NiTi have also been demonstrated by observing a change in electrical resistivity as the material is subjected to strain. By utilizing property changes as a result of thermal excitation in NiTi we expect to see an increase in stiffness related to the amount of NiTi embedded in the composite. The same material can be used to sense applied stress and strain as the stress induced phase transformation and elastic deformation changes the resistivity of the embedded NiTi alloy. Geometric stability of Al-NiTi composites is due to the shape memory effect of the embedded NiTi alloy. As temperature increases, the expansion of the aluminum matrix is opposed by the contraction of the NiTi wires. The counteracting strain of the matrix and NiTi reinforcement results in a partial transformation of the NiTi and a negative net strain of the composite. These behaviors are the subject of composite modeling efforts.

The low-temperature UAM process allows, for the first time, the creation of smart material based metal matrix composite structures with truly embedded multifunctionality. We have made Al-NiTi composites with shape memory NiTi wires and have conducted preliminary work in embedded Galfenol. Samples currently in development focus on creating additional Al-Galfenol composites. We will investigate the properties of these active composites as variable stiffness, sensing, and, with Al-NiTi composites, thermally invariant structures. Challenges will include the characterization of the interface between the aluminum and the embedded smart material for active build tests as well as increasing the proportion of embedded smart materials for increased functionality. Future work will extend the variable stiffness properties of the active composites to vibration damping. By increasing composite stiffness, natural frequency of a given system will also increase in a controlled manner. The sensing properties of the active composite will make it possible to measure internal stresses. By utilizing both properties, it may be possible to have both detection and suppression of vibration and noise accomplished with a single multifunctional composite.

7645-27, Session 6

Friction control in automotive seat belt systems by piezoelectrically generated ultrasonic vibrations

S. Bharadwaj, B. R. Burton, M. J. Dapino, The Ohio State Univ. (United States)

Active control of friction between sliding surfaces is a problem of significant interest in automotive applications. It has been shown that the friction force between sliding surfaces can be reduced by superimposing ultrasonic vibrations on the sliding velocity. The application of ultrasonics to actively modulate friction coefficients can be utilized in various vehicle systems (e.g., gear trains, sliding door/window mechanisms, seat belt systems, engine cylinders, brake systems, etc.) which often present contradicting requirements. Seat belts, in particular, are not adaptive and must be designed as compromise for various occupants and loading conditions. Mechanical pretensioners and load limiters partially address the trade-offs but at the expense of added mass and weight. This research investigates ultrasonic lubrication as a principle for enabling adaptive seat belts with controllable force at the interface between the D-ring and webbing. By precisely controlling the seat belt force during a crash event, superior restraint will be achieved.

This work shows that out-of-plane ultrasonic vibrations are effective in reducing friction in the case of seat belts. These vibrations are generated using an ultrasonic transducer under harmonic excitation and transmitted to the interface by a half-wavelength horn. The harmonic modulation in the normal force about a mean value results in a reduction in the average friction force at the interface.

Under normal loads up to 670 N at a speed of 0.025 m/s, 58% friction reduction is obtained. The trends show a decrease in the effect with increasing sliding velocity and increasing normal load.

n summary, this research investigates the potential of ultrasonic vibrations in controlling friction in an automotive seat belt system. By applying out-of-plane vibrations, frictional force at the interface between the D-ring and webbing is reduced. Small changes in friction force have a large effect on the chest force. Active control of friction would help improve the performance, efficiency, and lifetime of such sliding mechanisms.

7645-28, Session 6

Deformation modelling: embedding of communication device in SMC using numerical and FE models

E. Sulic, B. Pell, S. J. John, RMIT Univ. (Australia)

Use of SMC in manufacturing of vehicle body components for both structural and non-structural applications has been increasing over last 20 years, driven by OEM's and their need for lighter more fuel efficient vehicles. In parallel the number of entertainment and communication systems in the vehicles has also been expanding. Current services such as GPS, digital radio, and cellular phone, and future services such as vehicle-to-vehicle and vehicle-to-roadside communications require use of antennas to send/receive signals that are necessary for these services to function.

Development of one single wideband antenna that is capable of receiving all of the services listed above would represent significant advantage for any OEM. Taking this approach one step further and embedding such an antenna in a composite vehicle body panel 'smart composite component' would combine benefits of lower vehicle weight, lower assembly complexity and shorter assembly time. During initial embedding trials of such an antenna into SMC, a noticeable antenna deformation was observed, requiring the development of a numerical model capable of predicting this deformation.

Since the material under consideration is viscoelastic, a numerical model has been developed. The results obtained using this model are than compared to the experimental results, showing some correlation. Development of ANSYS FE model for the antenna embedding scenario is also used to validate numerical model and intended as an additional tool that can be used in further work on similar thermoset polymers. Results of all three (numerical, experimental and FE) methods are presented and discussed in this paper.

7645-29, Session 6

Design and analysis of supporting structure with smart struts for active vibration isolation

B. Kim, G. N. Washington, R. Singh, The Ohio State Univ. (United States)

(SMART VEHICLES WORKSHOP) This paper addresses the modeling and analysis of a supporting structure with smart struts in harsh vibratory environment. Especially, for most helicopters, gearbox vibrations have higher frequencies and multi-spectral contents causing serious structure-borne noise transmission. In order to deal with this problem, the dynamic responses of both passive supporting and active smart struts and their interactions are investigated.

Current active control methods are limited mostly to sinusoidal control and not appropriate to deal with modulated, multi-spectral vibration and noise signals. Thus, improved multi-spectral control algorithms are needed in order to attenuate amplitudes at higher gear mesh frequencies and sidebands simultaneously, along with new smart strut designs. Three novel model-based and nonlinear control algorithms are proposed and their performances are validated and compared with conventional techniques.

An experimental setup of a supporting structure is constructed with smart struts while incorporating appropriate boundary conditions. Conventional and novel control algorithms are being applied to demonstrate the feasibility from narrow and broadband control perspective with a single smart strut. Next, effects on changing the location of the smart inserts are investigated. Passive struts, active struts, and combinations of passive and active struts are analyzed and tested in order to determine the best combination for effective vibration attenuation. Additionally, geometric and kinematic effects due to asymmetric strut installations are observed regarding their location and orientation angles.

Techniques proposed in this research are expected to be implemented for various applications of active vibration and noise control including engineering structures and vehicles.

7645-30, Session 7

On the effects of electrical cables on structural dynamics of cabled structures: overview and results summary

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An overview of the study of the effects that electrical power and signal cables introduce on the dynamic response of cabled structures is presented, along with a summary of the most significant results. This was a three-year effort conducted at the Air Force Research Laboratory in the attempt to discover a set of practical approaches for updating well-defined dynamical models of cable-free structures, where knowledge of the cable type, position and tie-down method is known. While cables can be found on many different types of structures, the focus of this effort was on precision, low-damping, and low-first-modal-frequency structures. Dynamics of large precision structures can be significantly influenced by subsystems such as electrical cables and harnesses as the structural mass of those structures tends to become smaller and the quantity of attached cables continues to increase, largely due to the ever-increasing complexity of such structures. Contributions of cables to structural dynamic responses were observed but never studied, except for a low scale research effort conducted at the Air Force Research Laboratory, Space Vehicles Directorate. Presently cables are included in numerical models as nonstructural mass at best. These models are able to capture the system dynamics at low frequencies but do a poor job in mid to high frequency range. A more complex, yet practical approach to modeling cables was attempted in this effort. Studied cables adhere to space industry practices identified through an extensive industry survey. Experimental procedures and computational techniques for extracting structural properties of the cables were developed, and an extensive database containing cable properties was created. A simple beam was used as a two-dimensional test article to validate experimentally-derived cable properties and to refine the assumptions regarding boundary conditions. Finally, a bus-like panel with cables attached was designed, and finite element models were developed. The results of finite element models were then compared with the real structure that was tested in the laboratory. The comparison indicated that linear models can be used to predict the structural response of cabled structures.

7645-32, Session 7

High and low temperature cyanate ester shape memory polymers for space applications

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Cornerstone Research Group, Inc. (CRG) is designing and developing a family of space-qualifiable, cyanate ester shape memory polymers (SMP) for application in self-deployable space structures, space seals, aeroshells, and future aircraft systems. Having already demonstrated the feasibility of the current cyanate ester shape memory polymer (SMP) as a space-qualifiable material, CRG is refining its existing cyanate ester SMP to provide a material with a high level of utility across a range of aerospace applications. During a NASA Phase I SBIR, CRG was able to show that elastomeric cyanate ester materials having a very broad range of thermal and mechanical properties could be formulated using a relatively small amount of CRG's synthesized monomers and other low-cost, commercially available components. The cyanate ester elastomer materials exhibited excellent thermal stability, maintaining their properties to temperatures below -100C and as high as 300C. CRG's work with DoD and commercial aerospace customers has also helped to identify the proposed material as a durable, lightweight alternative to current state-of-the-art materials for space and aircraft systems.

7645-33, Session 7

A novel voice coil actuator for fast steering mirror system

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Voice coil actuator (VCA) has been widely used in many scanning and driving systems such as fast steering mirror (FSM) system , precision positioning platform, etc. The performance and parameters of VCA is the critical factor to the capability of the whole system. However, it still remains a crucial problem that the magnetic leakage has greatly depressed the performance of VCA. Recently, a novel VCA with concentration flux-line structure is presented .It can greatly reduce the magnet leakage so as to enhance the performance of VCA by a great deal. Another advantage of this VCA is it has much less electromagnetic interference on other electronic devices. In this paper briefly presents the theory model, finite element analysis (FEA) process, fabrication details and experiment results of the novel voice coil actuator which will be used in a fast steering mirror system. According

to the experiment results the output force of the VCA is 3.4N/A with a coil of 240 turns and the stroke is ±2.5mm. Driven by this VCA the scanning angle of the FSM can achieve ±4.6°in a close-loop system when the scanning frequency is 100Hz.

7645-34, Session 7

Characterization of varied geometry shape memory alloy beams

L. M. Gravatt, J. H. Mabe, F. T. Calkins, The Boeing Co. (United States)

Shape Memory Alloys (SMA) have proven to be a lightweight, low cost alternative to conventional actuators for a number of commercial applications. Future applications will require complex shape change and a detailed understanding of the performance of more complex SMA actuators is required. The purpose of this study is to validate engineering models and design practices of various SMA beams for future applications. Until now, SMA actuators have been fabricated into relatively simple beam shapes. Boeing is now fabricating beams in more complicated geometries in order to determine their strength and shape memory characteristics. These more complicated shapes will allow for lighter SMA actuators as well as provide more complex shape control. Some of the geometries evaluated include vertical and horizontal I-beams, sine wave and triangular wave beams, a truss, and a beam with perforated circular holes along the length.

A total of 11 beams were tested. These include simple rectangular beams made out of Aluminum, 55% NiTinol (NiTi), 57% NiTi, and 60% NiTi (% Nickel by wt.) as well as the more complex shapes made from 57% NiTi, Each sample was put through a number of characterization tests. These include a 3 point bend tests to determine stress/strain properties, low load thermal cycling to determine transformation temperatures, thermal cycling under an range of isobaric loads to determine actuator properties, and blocked force tests with varying preloads. Experimental results were then compared to modeled results.

7645-35, Session 7

Optimal control of piezoelectric elements for active vibrations suppression of blades

F. Botta, Univ. degli Studi di Roma Tre (Italy)

It is well known that the blade vibrations, in gas turbines, can involve failures and a reduction of the blade's life because of fatigue related phenomena. The adoption of the piezoelectric elements, during the last years, has received considerable attention by many researcher for its great potential in mechanical, aerospace, aeronautical and civil engineering. Recently also the studies of blades with a piezoelectric coat are beginning to appear. These could be very interesting with reference to the problems mentioned above, indeed this type of materials are very efficient for active control of vibrations.

The aim of this work is to propose an analytical method to drive piezoelectric elements for active vibrations control and, consequently, increasing fatigue life of blades. A quadratic objective function has been defined and a closed loop feedback control has been used. The modal shapes of the blade have been obtained by Galerkin method. The results are compared, and validated, with those obtained by a finite elements code.

7645-36, Session 7

Pneumatic artificial muscle and its application on driving variable trailing-edge camber wing

W. Yin, L. Liu, Y. Chen, Y. Liu, J. Leng, Harbin Institute of Technology (China)

Ailerons and flaps of most modern aircrafts are through mechanical hinges to control surface deflection in order to change the camber of the wing. The hinge devices are heavy, complex, and inefficient. To overcome these shortcomings, a flexible variable camber wing (FVCW) concept is presented, which is using the flexible wing skin technology, and cancels the traditional mechanical hinge.

As a novel bionic actuator, pneumatic artificial muscle has high power to weight ratio. In this paper, a variable trailing-edge camber wing drived by pneumatic artificial muscles (PAMs) is developed. It comprises a flexible skin, a sheet, and a honeycomb structure. The sheet is used to replace the traditional hinges to keep surface smooth during the camber changing. The role of flexible skin is to maintain the upper and lower surfaces smooth during the wing morphing. PAM can only be used to contract by a single way, unable to provide thrust and the flexure hinge is designed to obtain thrust. The variable camber wing model is manufactured to validate the morphing concept.

Wind tunnel test results show that the wing camber increases with increasing air pressure. When PAMs are filled with the pressurized air, the trailing-edge will be deformed downwards and the lift of aerofoil will be increased.

7645-37, Poster Session

Nanojoining and fabrication of nanojunctions using nano-particles

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Electrically conductive connections between nano building blocks are not straightforward. Instead of desired ohmic contacts, tunnel junctions or weak links of a high contact resistance typically at 200 kΩ for contact regimes on the order of 1 nm2, are often generated. So, the gap-sensitive contact resistance makes it difficult to join nano-building-blocks with repeatable performance in nano-devices. In this research double wall carbon nano tubes (DWCNT) were successfully joined to metallic electrodes to make a prototype of a low resistant, mechanically durable (higher fracture points) energy saving carbon nano tube filament light bulb. It was also shown that nano-size particles used in brazing of nano/micro-wires caused in reduction of brazing point around 100degC and increase the fracture point of the joint interface.

7645-38, Poster Session

Study on the novel Li polymer battery using polyindole electrode

Z. Cai, Tianjin Polytechnic Univ. (China)

This study is intended to develop a polyindole-based Li polymer secondary battery system, which has a high electromotive force together with excellent cycle property and is capable of fast charging and discharging. The batteries include polyindole as the cathode and Li as the anode. LiBF4 was used as the electrolytic solution with about 3.0V electromotive force. The battery achieves about 80~70mAh/g at discharge current densities of 10~103 A/m2. As the theoretical capacity of polyindole is 84 mAh/g, its capacity occurrence rate is 95% at the discharge current density of 10 A/m2 with a very high reaction rate. In addition, a discharge capacity at discharge current density of 103 A/m2 maintains 87% of capacity relative to that at 10 A/m2. This indicates that this battery is excellent in fast charge and discharge properties. The cyclic life of the battery, which is measured at the current density of 10 A/m2 with the discharge depth 60% at 25 , is about 30000 times. This shows the battery system has very excellent cycle property.

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7645-39, Poster Session

Research on thermo-mechanical properties of styrene-based shape memory polymer composite

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SMART VEHICLES WORKSHOP

Shape memory polymer (SMP) is a promising smart material which is under intensive investigation at present. Its advantages are the high strain recovery, low density, low cost and so on. However the low strength, low stiffness and low recovery stress are its disadvantages. So the styrene-based fiber reinforced shape memory polymer composite (SMPC) is fabricated and its mechanical behaviors are experimentally and theoretically studied in this paper. The glass transition behaviors of SMPC and SMP are investigated through tests of Dynamic Mechanical Analyzer (DMA). Three glass transition critical temperatures are defined and a method to determine their values based on DMA test is given out. A glass transition model is developed to predict the glass transition behaviors of SMPC and SMP. The material properties of strength and stiffness of SMPC and SMP are investigated through one-cycle three-point bending tests. Both bending strength and stiffness are calculated based on results of test. Experimental results show both strength and stiffness of SMPC are much higher than those of SMP. The material training behaviors of SMPC and SMP are investigated through multi-cycle three-point bending tests. A material training model is supposed to describe the material training behaviors of SMPC and SMP.

7646-02, Session 2

Iron oxide nanotubes: syntheses, characterizations, and magnetic behaviors

J. Xie, L. Chen, V. K. Varadan, Univ. of Arkansas (United States)

Nanotechnology involves controlled syntheses of nanomaterials, characterizations of their unique properties, and assemblies of functional nano-enabled devices. Magnetic nanotubes exhibit unique structural and magnetic properties and can have wide ranging applications because of their manipulation by external fields, substance encapsulation, and multifunctionalization. Here we report our efforts to synthesize and characterize the magnetic iron oxide nanotubes. Hematite (-Fe2O3) nanotubes, maghemite (-Fe2O3) nanotubes and magnetite (Fe3O4) nanotubes were obtained by different chemical techniques such as template synthesis and hydrothermal method. Scanning and transmission electron microscopy were performed to investigate their morphologies and structures. Their crystallinities were confirmed by using X-ray diffraction. To manipulate magnetic nanotubes, experiments were conducted to study their response when magnetic fields were applied. These magnetic nanotubes are expected to find versatile applications such as drug delivery, neuroscience, hypothermia treatments, etc.

7646-03, Session 2

Photoreduction of Au(III) to form Au(0) nanoparticles using ferritin as a photocatalyst

R. K. Watt, R. J. Hilton, J. Keyes, Brigham Young Univ. (United States)

Gold metal nanoparticles, have applications in bio sensing, technology, nano-tube formation, and cancer therapy, but are difficult to form reproducibly in well-defined size distributions. We report a method to synthesize gold nanoparticles within the ferritin cavity (8 nm) or using ferritin as a scaffold for coating gold on the outside surface (12 nm). The intrinsic iron oxide core of ferritin is a semi-conductor and light can excite electrons to an excitation band producing a powerful reductant when a sacrificial electron donor fills the hole. The target metal ions bind to ferritin and accept the excited electron. The reduction of the first ion creates a nucleation site making the reduction of other ions more favorable. Since light is a reactant, we can control the particle formation by the time of light exposure or by varying the wavelength of light. We can also vary the concentration of the photocatalyst, which also acts as a nucleation site for photo reduction of the metal ions. We have designed a modified spectrophotometer to monitor the rate of the reaction and have taken samples at various time points to characterize by electron microscopy (EM). This report will discuss the EM characterization of these samples as well as the kinetic characterization of the formation of the nanoparticles. Interestingly buffers and salt drastically alter the rate, extent and final product formed in these reactions.

7646-04, Session 2

Slow phase transformation of TiO2 nanorods

Y. Chen, K. S. Kang, K. H. Yoo, J. Nayak, J. Kim, Inha Univ. (Korea, Republic of)

Nanocrystalline TiO2 has chemical physical stability, high refractive index (2.5~2.7), and high photocatalytic ability and has been widely employed in photocatalytic, photoelectrochemical, and photovoltaic applications. Controlling the crystal phase is important for specific applications due to the phase dependence of photocatalytic, optical, and electronic properties. Wet chemical synthesis of TiO2 nanoparticles or nanorods has anatase phase. However, since the rutile phase is thermodynamically more stable than anatase phase, the anatase phase of TiO2 nanostructures can be transformed to rutile phase by thermal process. In this investigation, anatase pahse of TiO2 nanorods were synthesized with low temperature process. Diameter and length of the nanorods were 3~4 nm and 35 nm, respectively. The nanorods were annealed at 750 and 850 C to transform anatase phase to rutile phase. The transformation rate was extremely slow compared with other nanoparticle and thin films case. The cause of the slow phase transformation was analyzed in this article.

7646-06, Session 4

Nanotechnology for condition-based maintenance

J. Riddick, Army Research Lab. (United States); S. H. Choi, NASA Langley Research Ctr. (United States)

Condition-based maintenance (CBM) has emerged as an effective strategy for reducing the life cycle costs of existing and future Army vehicle systems. The advent of nanotechnology presents the opportunity to integrate prognostic and diagnostic capabilities necessary for CBM into vehicle systems without dramatic weight penalty. The present study details two separate nanotechnology-based systems to be used in CBM for Army vehicles. The first is a microspectrometer that uses nanotechnology to diagnose the state of vehicle engine components and on-board systems. Because of its small size, the microspectrometer can be placed in and around vehicle critical components in order to monitor the state of operation. The microspectrometer depends on RF and wireless power transmission to transmit measured data to be incorporated into CBM scheme. The second nanotechnology concept presented is thermo-electric (TE) materials that convert heat energy to electricity. The TE materials take advantage of an engineered lattice construction to generate electricity at a greater efficiency level than existing photovoltaic cells. The TE materials can be used to supplement the power demands of CBM systems in a variety of vehicles, from combustion engine vehicles to rotorcraft, and also any vehicle that operates in extreme temperatures or desert conditions.

7646-07, Session 4

A systems engineering approach to designing, modeling, and networking wireless nano sensors and systems

S. X. Mohan, Univ. of Arkansas at Little Rock (United States)

The wireless nano sensors networks and their real-world applications, such as structural health monitoring, implantable medical devices, intelligent highway systems, and others, combine sensing, networking, wireless communication, computation, and user interfaces in large complex systems. The design and implementation of such complex systems need to take into consideration their intended functionality, operational requirements, and expected lifetime. Systems engineering provides the design and implementation framework to successfully bring large complex systems into operation by integrating all engineering disciplines into a structured development process, starting with identification of the need, and defining the initial concept, to formulating the requirements to detailed design, development and then, implementation. Systems engineering facilitates the integration of multiple engineering disciplines and the communication process between them into a common framework

The design of nanosensor networks and systems encompass multiple areas of research, which include the following:

1. Design of nanosensors and modeling
2. Design of wireless interfaces
3. Design of reliable sensor networks that sense and collect data reliably
4. Design of backbone networks capable of reliably transporting

collected data to remote servers

5. Design of secure servers for data transfer

This paper provides a systems engineering models and analysis methodologies that are applied to the performance modeling of sensors and that can be adapted to large complex systems encompassing the above design steps. The paper models dynamic behaviors of nanowires, insights into the design of nanostructured wireless interfaces to provide wireless capability to nanosensors, and networking techniques that allows for failure recovery, data security, and QoS. Performmance results are provided based on either theoretical calculations or simulations.

7646-08, Session 5

Vibration control of beam using piezoelectric electro-active paper sensor

J. Kim, H. C. Lee, H. S. Kim, Catholic Univ. of Daegu (Korea, Republic of)

Cellulose-based Electro-Active Paper (EAPap) has been discovered as a smart material that can be used as a sensor and actuator. Its advantages include low voltage operation, light weight, low power consumption, biodegradability and low cost. EAPap is made of cellulose paper coated with thin electrodes. EAPap shows a reversible and reproducible bending movement as well as longitudinal displacement under electric field. The out-of-plane bending deformation is useful for achieving flapping wings, micro-insect robots, and smart wall papers. On the other hand, in-plane strains, such as extension and contraction of EAPap materials are also promising for artificial muscle applications.

Piezoelectricity is one of major driving mechanism of a cellulose-based EAPap. Although the potential of EAPap as a piezoelectric sensor is promising, the application of EAPap as a piezoelectric sensor has not been clearly studied yet. In order to use EAPap as a useful sensor, it is important to demonstrate EAPap as an actual piezoelectric sensor. Therefore, beam vibration control using EAPap sensor is investigated in the present paper. The EAPap sensor and piezoceramic patch will be attached on top and bottom surfaces of an aluminum cantilever beam. The beam vibration data will be obtained from EAPap sensor and the piezoceramic patch will suppress the beam vibrations as an actuator. Simple velocity feedback control algorithm will be used to control beam vibration. The final paper will present effective vibration suppression of the cantilever beam with EAPap sensor and propose EAPap as a promising piezoelectric sensor.

7646-09, Session 5

Environmental sensing in composite oxide semiconductor films

A. K. Pradhan, Norfolk State Univ. (United States)

Environmental Sensing in Composite Oxide Semiconductor Films

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Multicomponent semiconductor oxides mainly composed of elements like indium, zinc, tin or gallium are very promising new class of materials for application in transparent electronics, multifunctional sensors and other electronic applications. The major characteristic of these materials is high mobility, and the electrical behavior is a consequence of a conduction band primarily derived from spherically symmetric heavy-metal cation ns orbital with (n-1)d10 ns0 (n 4) electronic configuration. The carrier transport becomes insensitive to the degree of disorder of the film, and makes this class of quasi-polycrystalline and amorphous semiconductors attractive for numerous applications. We report here on the environmental sensing, such as ultra-violet-radiation and various gases of pulsed-laser deposited composite semiconductor films. These films demonstrate outstanding sensing capability from measuring the surface resistivity taking into account the absorption of sensing species. Our results show new possibilities for the low-cost high performance environmental sensors for numerous potential applications. The details of the results will be presented.

7646-10, Session 5

Formation of bismuth telluride with metallic nanoparticles for thermoelectric applications

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Bulk samples of Bismuth Telluride (Bi2Te3) nanoparticles clad in silver were made to observe the effect of cladding on thermoelectric properties of bulk samples. Silver nanoparticles suspended in aqueous solution were created, and pellets of Bi2Te3 were fabricated with these nanoparticles. Measurements of thermoelectric properties including Seebeck coefficient, electrical conductivity, and thermal conductivity, and materials characterization techniques including X-ray Diffraction and Scanning Electron Microscopy indicated enhancements in thermoelectric properties, attributed to the metallic nanoparticles located between Bi2Te3 grains.

7646-11, Session 5

Deposition of thin sodium-potassium niobate (NKN) films on piezoelectric cellulose EAPap

S. Jang, J. Kim, J. Kim, Inha Univ. (Korea, Republic of); J. Koh, Kwangwoon Univ. (Korea, Republic of)

Cellulose based EAPap is a natural piezoelectric polymer. However, compared to piezoelectric based ceramic materials e.g. PZT, it is necessary to enhance its piezoelectric property for device applications. Thin (Na,K)NbO3 (NKN) film NKN is a lead-free piezoelectric material which possesses a similar piezoelectricity and curie temperature compared with PZT. To enhance the piezoelectricity of EAPap film, thin NKN layer was deposited on cellulose paper by RF magnetron sputter. In this paper, we report the optimized deposition condition of NKN layer growth on EAPap without damages. The structural analysis and the optical properties of NKN deposited cellulose films were investigated by XRD, AFM, FTIR, UV visible measurements. Also, the electrical properties and its piezoelectricity of the composite cellulose film were characterized. The enhanced properties of composite cellulose material can be used for acoustic based sensors, flexible electronics and piezoelectric actuator.

7646-12, Session 5

Growth and properties of PZT -based perovskite multilayers for sensor applications

R. B. Konda, Norfolk State Univ. (United States)

Polarization properties, which depend on different voltages and different temperatures, crystal structures, and surface morphology have been demonstrated for PZT/Pt/Si, STO/PZT/STO/PZT/Pt/Si, and BTO/STO/BTO/STO/Pt/Si multilayer perovskite samples. The effects of the thickness of the PZT film layer also investigated for PZT/Pt/Si multilayer sample. The multilayer perovskite samples were fabricated with using magnetron sputtering and pulsed laser deposition (PLD) techniques. PZT/Pt/Si samples were fabricated with different PZT film thickness. Surface morphology was investigated by atomic force microscopy (AFM). The hysteresis loops of PZT/Pt/Si multilayer samples were obtained by Probe Station which was connected to ferroelectric

analyzer.The other multilayer samples were compared for their surface morphology. Characterization of crystal structures and polarization of varying thickness samples are under progress

7646-13, Session 5

Carbon nanocomposite-based contact mode interdigitated center of pressure sensor

T. Xu, C. Park, N. Guerreiro, J. H. Kang, J. S. Harrison, J. Hubbard, Jr., National Institute of Aerospace (United States)

A carbon nanocomposite-based contact mode interdigitated center of pressure sensor (CMIPS) has been developed. The experimental study demonstrated that the CMIPS has a capability to measure the overall pressure as well as the center of pressure in one dimension, simultaneously. A theoretical model for the CMIPS is established here based on the equivalent circuit of the CMIPS configuration as well as the material properties of the sensor. The experimental results match well with the theoretical modeling predictions. This theoretical model will provide guidelines for future advanced sensor development based on the CMIPS. A system mapped with two or more pieces of the CMIPS can be used to obtain information from the pressure distribution in multi-dimensions. As an intelligent system component, the inexpensive CMIPS can be used broadly for improving sensing and control capabilities of aircraft and measurement capabilities of biomedical research as well as chemical industries. The details about experimental and theoretical investigations for the CMIPS will be presented in this paper.

7646-16, Session 7

Nanowire gas sensors and wireless sensing network for electronic-nose development

H. Yoon, P. T. Hankins, S. Oh, Univ. of Arkansas (United States); C. L. Brantley, U.S. Army Research, Development and Engineering Command (United States); E. Edwards, P. B. Ruffin, U.S. Army Aviation and Missile Research, Development and Engineering Ctr. (United States); Y. M. Kim, V. K. Varadan, Univ. of Arkansas (United States)

In this research, we developed nanowire gas sensors and wireless sensing system with Zigbee and Wi-Fi protocols. Nanowire gas sensors have been developed with large surface area of tin oxide on vertically aligned nanowires and part per billion level of solvent vapor sensitivity has been obtained. With the wireless sensing system, resistive electrical signals from the sensors were input to a Zigbee wireless module and the sensing signals were transmitted to Wi-Fi for recording signals outside. This wireless gas sensing system has been tested various condition including the environment with isopropyl alcohol vapors for the early detection of explosion and hydrogen sulfide and ammonia gases related to bacteria metabolism. Currently, research for the integration of these two systems on a chip is being conducted for the development of electronic nose module in a hand held system for high sensitivity monitoring and rapid identification of gas species.

7646-17, Session 7

Nanocalorimeter arrays for detection of biohazard samples

L. Zuo, Stony Brook Univ. (United States)

With the increased threat of biochemical terrorist attacks and concern of environment pollution, it is necessary to identify small volume of biohazards and provide early detection. The detection and analysis of biohazard material are possible using biological thermodynamical recognition in calorimetry. However, the long measurement times and large sample requirements of the existing technology make it difficult to screen the biohazard samples rapidly for early detection. In this paper, we design an ultrasensitive nanocalorimeter array for accurate and rapid evaluation of biohazard materials at the early stage of biological attacks or environment threaten. Here we propose an isothermal titration nanocalorimeter arrays with significantly reduced sample volume 1-2uL, high temperature sensitivity 10 uK, and high throughput. The nanocalorimeter array contains SU-8 microcantilevers and free standing thin polymer diaphragms, which integrate integrated thermistors of low thermal noise and resistive microheaters for power compensation. The proposed label- and immobilized free technology will enable direct and high-throughput evaluation of the Gibbs free energy, enthalpy, entropy, and specific heat of the interaction of biohazard samples and biological recognition molecules.

7646-18, Session 7

Homeland security monitoring sensors and early warning relay and diagnostic system

V. K. Varadan, Univ. of Arkansas (United States)

No abstract available

7646-19, Session 7

PEDOT:PSS coated SWNT based gas sensor

S. Badhulika, Univ. of California, Riverside (United States)

PEDOT :PSS coated singlewalled carbon nanotube gas sensors

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Single walled carbon nanotubes (SWNTs) have been put into use for sensing gases and vapor phase analytes because of their unique properties like small size,low power consumption, stability and high specific area. The sensing behavior is mainly due to

the fact that the SWNT consists solely of surface such that every single carbon atom is in direct contact with the environment and hence changes in their local environment has a direct impact

on the electronic properties of the SWNTs that can be easily identified.

However, certain limitations like inability to identify gases with low adsorption energies and low concentrations led to the development of hydrid sensors that combine the merits of a conducting polymer like solution processibility and flexibility with those of SWNTs that act as a conduit for charge transfer.

Our work involves the fabrication of polymer PEDOT :PSS -poly(3,4-ethylene dioxythiophene):poly(styrene sulfonic acid) coated SWNT gas sensors and subsequent characterization of their electronic properties at room temperature .

The hybrid sensors displayed a change in resistance when exposed to varying concentrations of analytes and hence showed promise as conductometric sensors.

The underlying mechanism of sensing was also investigated by using them as chemFET devices.

PEDOT :PSS coated SWNTs exhibited better , on average,sensitivity to lower concentrations of a series of vapor phase analytes that were put for sensing than pristine SWNT gas sensors .

7646-20, Session 7

Flexible strain sensor based on carbon nanotube rubber composites

I. Kang, J. H. Kim, K. T. Lim, Pukyong National Univ. (Korea, Republic of)

Electrically conducting rubber composites (CRC) with carbon nanotubes (CNTs) filler have received much attention as potential materials for sensors. In this work, Ethylene propylene diene M-class

rubber (EPDM)/CNT composites as a novel nano sensory material were prepared to develop flexible strain sensors that can measure large deformation of flexible structures. The EPDM/CNT composites were prepared by using a Brabender mixer with multi-walled CNTs and organo-clay. A strain sensor made of EPDM/CNT composite was attached to the surface of a flexible beam and change of resistance of the strain sensor was measured with respect to the beam deflection. Resistance of the sensor was change quite linearly under the bending and compressive large beam deflection. Upon external forces, CRC deformation takes place with the micro scale change of inter-electrical condition in rubber matrix due to the change of contact resistance, and CRC reveals macro scale piezoresistivity. It is anticipated that the CNT/EPDM fibrous strain sensor can be eligible to develop a biomimetic artificial neuron that can continuously sense deformation, pressure and shear force.

7646-21, Session 8

A digital logic nanowire for reliability enhancement

S. C. Lee, Univ. of Oklahoma (United States)

Due to the many random factors from thermal fluctuations to wave interference, computational perfection in nanoICs is difficult to achieve. Defects and faults arise from instability and noise proneness of nanoICs, which lead to unreliable results. A probabilistic computational model is needed to reduce such errors and to achieve more reliable computation. The probabilities of the outputs of this model can be calculated by the arithmetic expressions of the Boolean functions.

This paper presents a method for transforming a low reliability nanocircuit made of unreliable nanogates into a high reliability nanocircuit without the need of any special reliable nanogates. A class of nanocircuits, called reliability enhancement nanocircuits (RENC)is introduced. Each RENC is a simple logic circuit with a single input and output. It is shown that with a proper setting of the “logic threshold value” from the output probability function of RENC, which determines logic value 0 or 1 for the input and output, the output reliability of RENC can be higher than its input reliability. Thus, when an RENC is connected to each output of a low reliability nanocircuit, the reliability of the entire circuit can be enhanced. By cascading n numbers of RENCs, we can form a reliability enhanced nanowire (RENW). It is also shown that by connecting each output of a low reliability nanocircuit with an RENW, the reliability of the nanocircuit can be raised to any desirable level. Illustrative examples are given. This method is applicable to any digital nanocircuit design using any nanotechnology.

7646-22, Session 8

A programmable second order oversampling CMOS sigma-delta analog-to-digital converter for low power bio- and chemical sensor interface electronics

R. Soundararajan, A. Srivastava, Louisiana State Univ. (United States)

In many sensor interface circuits used in biomedical, pharmaceutical, wireless sensor networks or automotive, data conversion demands great care and stringent requirement for power consumption. In this work a programmable oversampling sigma-delta ADC has been designed for effective use in low power interface electronics since the resolution has a direct impact on the power consumption. A computer simulated model of integrated sensor system consisting of carbon nanotube field-effect transistor and a programmable oversampling sigma-delta ADC will also be presented for low power bio- and chemical sensing applications.

Recently, Srivastava and Anantha have reported a programmable CMOS sigma-delta ADC using a first order modulator and second order cascaded integrator comb filter. In this work, we have designed a programmable oversampling sigma-delta ADC in 0.5 µm CMOS process using a discrete-time 2nd order sigma-delta modulator and a programmable 3rd order CIC decimator.

The low power integrated sensor system will be used to show the variation of the power consumed for different resolutions of the ADC. Since the designed ADC can be operated at three different resolutions of 9, 12 and 14 bits by varying the oversampling ratios, the power consumed by the integrated sensor system can also be varied significantly. Hence, this system proves to be efficient and promising for application of integrated sensor system in bio- and chemical applications for wireless sensor networks.

A. Srivastava and R. R. Anantha, “A Programmable Oversampling Sigma-Delta Analog-to-Digital Converter,” 48th IEEE Midwest Symposium on Circuits and Systems, vol. 1, pp. 539-542, 2005.

7646-23, Session 8

Probabilistic behavior and information measures of sequential nanoICs

S. C. Lee, Univ. of Oklahoma (United States)

Since the advent of nanotechnology, not only the size of the circuit has been reduced to nanoscale but also the fundamental laws that govern the circuit behavior have been changed: from the conventional Kirchhoff’s voltage and circuit laws to the laws of quantum mechanics. Due to high noise-to-signal ratio and the randomness nature of the deterministic models, probabilistic models are used to model the circuit behavior of nanocircuits. When the noise-to-signal ratio of a nanocircuit is kept below a certain threshold, the circuit can still perform normally. In order to design fault-tolerant computing nanomachinery, we must first realize the importance of the understanding of the probabilistic behavior of nanocircuits and then know how to extract their information contents. The probabilistic behavior and information measures of combinational nanoICs have recently been studied.

The purpose of this paper is to investigate the probabilistic behavior and information measures of sequential nanoICs which are in general much more complex and have not been previously studied. Yet, it is vitally important for the analysis and design of future fault-tolerant nanocomputing machineray. To extract information from sequential nanoICs in nanospace of a noisy environment, it is found that the most appropriate measure of information is the measure of entropy. The results of the study of probabilistic behavior and information measures of various types of flip-flops and other sequential nanoICs such as registers, counters, etc. in noisy nanospace are reported with detailed illustrative examples.

7646-24, Session 8

Quantum state transition diagram: a bridge from classical computing to quantum computing

L. R. Hook IV, S. C. Lee, Univ. of Oklahoma (United States)

Ever since Feynman’s paper (Simulating physics with computers, Internat. J. Theor. Phys., 1982)suggesting the possible advantages of a quantum computer, research into quantum computation has received a lot of attention. Shor’s algorithms (Algorithms for quantum computation: discrete logarithms and factoring. Symp. on Foundations of Computer Sciences, 1994) showed that one could factor integers with a quantum computer in polynomial time. More importantly, Shor’s discovery proved a case where a quantum computer is more powerful than a classical computer for specific and relevant algorithms. One of the proposed architectures for the construction of a quantum computer relies on quantum cellullar automata (QCA) which has recently been accepted as the standard.

This paper proposes a new structure, a quantum analog to the classic state diagram, called quantum state transition diagram (QSTD). In QSTD, each node corresponding to each particular state has the function of summing nodes and each transition link carries the value of the original node, multiplied by a multiplier, M(i,j), where i and j are, respectively, the destination and source nodes, which is determined from the transformation matrix of the QCA. A general procedure for constructing QSTD is presented with illustrative examples including the constructions of QSTD for the Hadamard gate, the controlled-NOT

gate, the two-cell partitioned QCA and other QCA devices. The results of this paper may provide computer scientists and engineers with a useful design tool to construct molecular nanocomputers using QCAs and, at the same time, serve as a bridge between classical computing and quantum computing.

7646-25, Session 9

Power beaming to a micro aerial vehicle using an active phased array

H. Sawahara, A. Oda, A. Diallo, K. Komurasaki, Y. Arakawa, The Univ. of Tokyo (Japan)

A power beaming system to a Micro Aerial Vehicle (MAV) using 5.8GHz microwaves has been developed. With this wireless power system, a battery on a vehicla is charged by receiving a microwave beam while the vehicle is circling above a phased array transmitter. Then, it can fly over the area struck by disaster, for example, continuously without landing and take-off for recharging.

The schematic of the system developed in our laboratory consists of three sub-systems; a pointing system, a tracking system, and a receiving system. A microwave beam is pointed to the MAV using the phase information of its pilot signal. Software retro-directive function has been realized through a PC control. An electric motor for a propeller is driven by the power received on a rectenna array.

Steering of a 5.8GHz microwave beam was achieved by controlling the phase of microwaves emitted from the multiple antennas called phased array system, not by mechanical control of the antenna's attitude. Our phased array is composed of five horn antennas.

In the tracking system, three patch antennas receive the pilot signal of 2.45GHz microwave sent from the MAV. Two pairs of patch antennas were aligned in the x and y directions with the distance of . The incident angle of the pilot signal is analyzed using a PC.

In the receiving system, a conventional patch rectenna array has been replaced by an ultra-light and flexible rectenna array, which will be an indispensable technology to realize real "micro" robots, such a MAVs.

7646-26, Session 9

Enhanced thermoelectric figure of merit in nanostructured SiGe alloys

H. Kim, National Institute of Aerospace (United States); Y. Park, George Washington Univ. (United States); G. C. King, NASA Langley Research Ctr. (United States); K. Lee, Federal Highway Administration (United States); S. H. Choi, NASA Langley Research Ctr. (United States)

Practical use of thermoelectric devices hinges on their performance measured by the figure of merit. We focus on SiGe-based alloys for high temperature application. DC and RF sputtering methods were used to grow a SiGe layer and SiGe nanocluster-structured array on c-plane sapphire substrate in various experimental conditions. In the case of a SiGe layer, we were able to control the epitaxial growth to make a [111]-oriented single crystalline SiGe layer or a [111]-oriented highly twinned SiGe layer (60°-rotated crystal) on c-plane sapphire which is baseline to lower the thermal conductivity for high figure of merit. Also, we grew a SiGe array, which is composed of many nanocluster-structures scaling up to several tens of micrometers. Dense population of nanoclusters and nanorods is regarded enhancing the scattering frequency of the phonons, thus reducing the thermal conductivity and consequently increasing the figure of merit.

7646-27, Session 9

Rectennas performance based on substrates for bio-medical applications

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Since many researchers have recently involved to develop bio-sensors , it is critical to provide an alternative power source for the devices in order to provide maneuverability and flexibility of the sensors. In these applications, it is important to evaluate performance of rectennas through humans or animals. In addition to that, biological effects of humans and animals are critical issues as well.

In this paper, we designed various rectennas with different substrates, and tested for evaluation of the performance. We studied the influences of microwave on rectenna through a pig skin when we apply this concept into sensors and devices under the skins for medical applications.

7646-28, Session 9

Reliability considerations in switchable PLL frequency synthesizers for wireless sensor networks

Y. Liu, A. Srivastava, Louisiana State Univ. (United States)

A wireless sensor network is implemented by multiple sensor nodes collecting analog information and communicating data between the center control stations to each node. In wireless sensor system, a low cost, wide frequency range and large bandwidth RF communication system is required which uses phase-locked loop (PLL) as a frequency synthesizer. A new strategy of switchable phase-locked loop frequency synthesizer is designed and fabricated in 0.5 μm CMOS process to analyze the chip reliability under hot carrier effect (HCE) and negative bias temperature instability (NBTI). The switchable PLL frequency synthesizer can work in a wide frequency range from 320 MHz to 1.15 GHz and can be integrated in RF transmitter and receiver of the sensor systems. As device size shrinks and channel electric field increases, interface and oxide traps play important roles affecting the performances of devices and thus the reliability. HCE and NBTI are known to be one of the critical reliability issues in sub-micron and nanometer CMOS technologies. In this paper, jitter and phase noise performances of both open loop VCO and PLL under HCE and NBTI are investigated. The tuning frequency of open loop VCO decreases about 200 MHz after 4 hour hot carrier stress and decreases about 140 MHz after 4 hour NBTI stress. The phase noise of PLL frequency synthesizer increases about 1-2 dBc/Hz under both HCE and NBTI stresses. The results will be extrapolated in better understanding and design of reliable wireless sensor networks.

7646-29, Session 9

The application of wireless sensor system on security network

S. Oh, H. Kwon, H. Yoon, V. K. Varadan, Univ. of Arkansas (United States)

In this research we developed wireless sensor system for security network. We have used geophone to detect seismic signals which are generated by footsteps. Geophones are resonant devices. Therefore, vibration on the land can generate seismic waveforms which could be very similar to the signature by footstep. The signals from human footstep have weak signals to noise ratio and the signal strength is subject to the distance between the sensor and human. In order to detect weak signals from footstep, we applied 2-stage amplifying circuit which consists of active and RC filters and amplifiers. The bandwidth of filter is 0.7Hz-150Hz and the gain of amplifier is 1000. The wireless sensor system also developed to monitor the sensing signals at the remote area. The wireless sensor system consists of 3 units; wireless sensor unit, a wireless receiver unit, and a monitoring unit. The wireless sensor unit transmits amplified signals from geophone with Zigbee, and the wireless receiver unit which has both Zigbee and Wi-Fi module receives signals from the sensor unit and transmits signals to the monitoring system with Zigbee and Wi-Fi, respectively. By using both Zigbee and Wi-Fi, the wireless sensor system can achieve the low power consumption and wide range coverage.

7646-30, Session 9

Software structure for broadband wireless sensor network system

H. Kwon, S. Oh, H. Yoon, V. K. Varadan, Univ. of Arkansas (United States)

This paper describes software structure for a wireless sensing system using wireless LAN and Zigbee. The system has the benefit of Zigbee sensor network measuring multiple sensors and the advantage of wireless LAN with high data rate and broadband communication. This system has three main software structures. The first part of software structure comprises sensing data conversion and the second part is to gather the sensor data through wireless Zigbee and to send the data using wireless LAN. The second part consists of Linux packages software based on Samsung2440 CPU, which has ARM9 core. The Linux packages include bootloader, device driver, kernel, and application. The applications are TCP/IP server program, wireless Zigbee program, and wireless LAN program. The last part of software structure was developed by using Visual C++ to communicate the sensor data through TCP/IP client program and to display graphically measured data; the sensor data is measured on 100Hz sampling rate and the measured data has 10bit data resolution. The wireless data transmission rate per each channel is 1.5kbps. Thus, the wireless data transmission rate of this system that has 3 sensors is totally 4.5kbps.

7646-57, Poster Session

Micro-electronic circuit design for amplification and modulation in a MEMs human blood-pressure sensor

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In this paper the design and simulation of an integrated circuit for electric signal amplification and digitalization from a MEMS human blood pressure sensor is presented. The signal consists on a variable voltage from 0 to 10 mV, 1 mA and frequency from 50 to 500 Hz. Its simple but effective design consists on an operational amplifier (op-amp) configured as a differential amplifier which amplifies the signal (up to 3V and 10mA), originating from a Wheatstone bridge in the MEMS sensor, and then this signal is digitalized and modulated via pulse width modulation (PWM). The technology used in this circuit is MOSIS AMI 1.5 um. The circuit was designed with a two-stage Op-Amp used along several stages of the system. The use of a differential amplifier, the two-stage Op-Amp and the PWM simplifies the design and makes it compact due to the use of fewer components (40 transistors). The use of PWM facilitates processing of the signal in later stages. The result is the design and simulation of the circuit. It consists in the schematic diagram and layer diagram with all the rules specified in the process MOSIS AMI 1.5 um. Electric and LTspice software were used in the design and simulating of the circuit. A full description of the design philosophy, design criteria, output traces and curves and results will be presented.

7646-58, Poster Session

Synthesis and characterization of composite of gold nanoparticles attached ZnO nanorods

K. Zhang, Norfolk State Univ. (United States)

Gold nanoparticles, ZnO nanorods and there composite were synthesized through wet-chemical route at low temperature and ambient pressure. The nanostructures and composite were examined by X-ray diffraction, Scanning electron microscopy, transmission electron microscopy, photoluminescence and UV-visible absorption spectra. The gold nanostructures were tightly attached to the nanorods surface of ZnO in the composite. The characterization showed that the nanorods were uniformly distributed and the gold nanostructures were completely controlled. The results demonstrated that the nanostructures and the composite display luminescent behavior and the optical absorbance was enhanced by the gold nanoparticles in the range of visible light owning to the surface plasmon resonance phenomena in the gold nanoparticles. The composite of gold nanoparticles attached ZnO nanorods may be utilized for biomedical applications. The detail results will be discussed.

7646-61, Poster Session

Simple theoretical analysis of the thermoelectric power under strong magnetic quantization in superlattices of non-parabolic semiconductors with graded interfaces

S. Singharoy, JIS College of Engineering (India)

The theoretical results of our paper can be used to determine the TPM for SLs and the constituent bulk semiconductors in the absence of magnetic field. It is worth remarking that this simplified formulation exhibits the basic qualitative features of the TPM for the SLs and the constituent materials respectively. Finally it may be noted that the aim of the present work is not solely to investigate the TPM but also to suggest the experimental determinations of the Einstein relation for the diffusivity-to-mobility ratio, the Debye screening length and the carrier contribution to the elastic constants for materials having arbitrary band structures which, in turn, is again dimension independent.

7646-62, Poster Session

Dynamic behavior of double-walled carbon nanotubes conveying viscous fluid based on nonlocal elastic theory

Y. Zhen, B. Fang, T. Yang, Harbin Institute of Technology (China)

Because of perfect hollow cylindrical geometry and excellent mechanical properties, the carbon nanotubes (CNTs) hold substantial promise in nanobiological devices and nanomechanical systems such as fluid storage, fluid transport, and drug delivery. Fluid flow inside CNTs raises a significant and challenging research topic. On the other hand, the influence of internal moving fluid on overall mechanical behavior is another major topic. Based on the theory of Euler-Bernoulli beam model, the instability of a free-free double-walled carbon nanotubes (DWCNTs) conveying fluid is studied. The viscosity of fluid and the nonlocal effect are incorporated in the formulation, and the Galerkin discretization method is used to solve the coupled equations of the motions. The critical flow velocities, associated with divergence and restabilization, are obtained. As the increase of fluid velocity, the system experiences stability, divergence, and restability states. Numerical simulations show that the van der Waals (vdW) interactions and the internal moving fluid play a significant role in the natural frequency and the stability of DWCNTs. The critical velocities with no vdW interactions are much smaller than those considering vdW interactions. It means that the system is more stable with the vdW interactions(Fig.1). The influence of viscosity, nonlocal effect, aspect ratio and surrounding elastic medium are also analyzed in detail. Under different dimensionless viscosities, there is no obvious difference with the increase of fluid velocity until the dimensionless fluid velocity is up to 14.20. The natural frequency of the DWCNTs decreases as the fluid viscosity increased when the dimensionless velocity is greater than 14.20 (Fig.2). As the nonlocal parameter increased, the natural frequency decreases under the condition that the system is stable. Also, the unstable region of velocity becomes greater when the nonlocal parameter increased (Fig.3). The aspect ratio of DWCNTs has important influence on the stability of the system. The system gets more stable as the aspect ratio of the DWCNTs increased (Fig.4). When the Winkler constant of the elastic medium is 1 KPa or 1Mpa, the natural frequency and the stability of the system is almost the same. When K=1GPa or 10GPa, the critical velocity of the system is greater

than 1MPa. This implies that the surrounding elastic medium also plays a role in the stability of DWCNTs (Fig.5).

7646-63, Poster Session

Analysis of the effect of both specimen size and grain size on the tensile strength of the polycrystalline metallic materials

B. Jung, H. Lee, H. Park, Pohang Univ. of Science and Technology (Korea, Republic of)

A modified strain gradient plasticity theory is proposed based on the mechanism-based strain gradient (MSG) plasticity. This study is motivated by nonhomogeneity of polycrystalline materials. We believe that the geometrically necessary dislocations (GND) are generated on slip system as well as grain boundary to accommodate the deformation shape with internal stress. The new theory differs from the MSG plasticity in consideration of the GND on grain boundary and free surface effect of polycrystalline materials.

Using the proposed model, an analysis of the effect of both specimen size and grain size on the tensile strength of the polycrystalline materials is carried out.

7646-64, Poster Session

Simple theory of the interband optical absorption co-efficient in semiconductors in presence of an electric field and its dependence on a longitudinal magnetic field

S. Singharoy, JIS College of Engineering (India)

The oscillations in OAC is not due to “Stark” ladder (as claims Callaway) but due to the consideration of -dependence of optical matrix element (OME) in presence of electric field (Fig. 2c) as well as in presence of electric plus parallel magnetic fields as it is obvious from theoretical predictions.

In the case of the presence of Electric plus parallel magnetic fields, the effect of electric field on OAC is more prominent than the case of parallel magnetic field

7646-65, Poster Session

Thermal sensors based on nano porous silicon

J. Lin, St. John’s Univ. (Taiwan); W. Tsai, National Cheng Kung Univ. (Taiwan)

Nano porous silicon (NPS), consisting of many nano pores and high-aspect-ratio silicon (Si) pillars, was prepared by electrochemical etching in a hydrogen fluoride (HF) and a potassium hydroxide (KOH) solution. NPS can be designed to control heat transfer on its surface and can lead to a better efficiency of thermal sensors because of the high surface to volume ratio and considerable quantities of porosities of NPS. In this study, the thermal sensors based on NPS were explored. The size of the pores by adjusting process parameters like the formation conditions of NPS and the sensitivities and responses of thermal sensors were presented and discussed.

7646-66, Poster Session

Ferritin as a photocatalyst in an artificial photosynthesis system

R. J. Hilton, J. Keyes, R. K. Watt, Brigham Young Univ. (United States)

Alternate fuel sources are becoming increasingly important as the reserve of fossil fuels decrease. We describe a bio-photocatalyst based on the iron storage protein ferritin. The ferritin protein naturally sequesters ferrihydrite inside a spherical 12 nm protein shell. Ferrihydrite is a semi-conductor material that functions as a photocatalyst in aqueous solvents. Ferritin has been shown to photoreduce Au(III) and Cu(II) ions in solution to form 10-30 nm Au(0) and Cu(0) nanoparticles. Citrate acts as a sacrificial electron donor to supply electrons for the photoreduction. We describe studies designed to understand the mechanism of this catalyst in order to improve the efficiency of the reaction. We have developed a spectrophotometric assay to simultaneously illuminate the sample and kinetically monitor the formation of products. We report that buffers containing sulfur significantly increase the rate of the reactions. The absence of salt can completely inhibit the reaction. Control reactions with colloidal ferrihydrite nanoparticles do not catalyze the photochemical reaction but produce a black magnetic precipitate indicating that the protein shell has an important function in nanoparticle formation. To substantiate this hypothesis, studies were done with H and L homopolymers of ferritin. The results show that the H homopolymers were more effective in nanoparticle formation than the L homopolymers. Interestingly, the homopolymers were more efficient than the natural heteropolymer of H & L ferritins found in horse spleen ferritin. Finally, the sacrificial electron donor citrate appears to play an additional role as an intermediate in the photochemical reaction.

7646-31, Session 10

Multi-walled carbon nanotubes covalent bonded cellulose composite chemical vapor sensor

S. Yun, S. Y. Yang, J. Kim, Inha Univ. (Korea, Republic of)

A cellulose solution is prepared by dissolving cotton pulp in LiCl/DMAc solution. Functionalized multi-walled carbon nanotubes (MWCNTs) are reacted with N, N-Carbonyldiimidazoles to obtain MWCNTs-imidazolides. By acylation of cellulose with MWCNTs-imidazolides, MWCNTs were covalently bonded on cellulose chains. Using the product, regenerated cellulose with covalently bonded MWCNT (RC-MWCNT) paper is fabricated with mechanical stretching to align MWCNTs with cellulose. Finally, inter-digital (IDT) comb electrode is formed on the paper via lift-off process. We expect that the presence of alignment as well as covalent bonds of MWCNTs on RC-MWCNT paper sensor will play an important role in remarkably changing chemo-electrical properties in response of absorption of the volatile vapors. As exposing volatile chemical vapors corresponding to propanol, butanol, methanol and ethanol, the chemo-electrical properties of RC-MWCNT paper sensor will be analyzed with respect to selectivity, reproducibility and stability.

7646-32, Session 10

Integration of OLEDs in biomedical sensor systems: design and feasibility analysis

P. Rai, P. S. Kumar, V. K. Varadan, Univ. of Arkansas (United States)

Organic (electronic) Light Emitting Diodes (OLEDs) have been shown to have applications in the field of lighting and flexible display. These devices can also be incorporated in sensors as light source for imaging/fluorescence sensing for miniaturized systems for biomedical applications and low-cost displays for sensor output. The current device capability aligns well with the aforementioned applications as low power diffuse lighting and momentary/push button dynamic display. A top emission OLED design has been proposed that can be incorporated with the sensor and peripheral electrical circuitry, also based on organic electronics. Feasibility analysis is carried out for an integrated optical imaging/sensor system, based on luminosity and spectrum band width. A similar study is also carried out for sensor output display system that functions as a pseudo active OLED matrix. A power model is presented for device power requirements and thermal constraints. The feasibility analysis is also supplemented with the discussion about implementation of ink-jet printing and stamping techniques for possibility of roll to roll manufacturing.

7646-33, Session 10

Cellulose polypyrrole-ionic liquid (CPIL) nanocomposite for highly durable, biomimetic electro-active paper actuator

S. K. Mahadeva, J. Kim, J. Kim, Inha Univ. (Korea, Republic of)

Cellulose has received much attention as a emerging smart material, named as electro-active paper (EAPap), which can produce a large bending displacement with applied external electrical field. In spite of many advantages over other reported electro active polymers, the material improvement as an actuator is required due to the poor performance under ambient humidity condition and the degradation of performance with actuating time. To improve the performance and durability of EAPap, nano-layered PPy layer into cellulose EAPap was formed by in-situ polymerization technique. Cellulose-PPy-IL nanocomposite based EAPap actuator showed nearly 100% improvement of the actuator performance compared that of pure cellulose based EAPap actuator systems. In present paper, we have successfully developed the highly durable EAPap actuator working at ambient condition with large displacement output.

7646-34, Session 11

Photoresponsive hydrogel microvalve activated by bacteriorhodopsin proton pumps

K. M. Al-Aribe, G. K. Knopf, The Univ. of Western Ontario (Canada)

Light driven and optically controlled microfluidic chips have several advantages over thermal, electrical or electromechanical designs. Optical systems are free from current losses, resistive heat dissipation, and friction forces that can greatly diminish the performance and efficiency of the active microsystem components (eg. pumps and valves). An organic photoelectric thin film that can control the expansion and shrinkage of a pH sensitive hydrogel microvalve is introduced in this paper. The organic film is fabricated from bacteriorhodopsin (bR), a light sensitive protein found in the salt marsh bacteria Halobacterium salinarium. The bR protein acts as proton pump that transports hydrogen ions across the cell membrane when exposed to visible light. However, for photon to ion flow efficiency, it is necessary that all bR molecules are oriented in the same direction. In this research, the directional proton pumps are self-assembled on gold coated porous substrates using biotin and streptavidin for selective molecular labeling and adsorption. The flow of ions from the photon activated bR changes the pH value of the ionic solution around the HEMA-AA hydrogel microvalve. The chargeable polymeric network undergoes a geometric phase transition when the pH of the ionic solution is shifted to the phase transition point pKa. Preliminary tests show a measurable change in pH of the ionic solution (6.5 to 8.0) when bR proton pumps were exposed to a 568nm light beam at 18mW for 20 minutes. Furthermore, the resultant pH gradient induced a 40% volume change in the polymer microvalve.

7646-35, Session 11

Synthesis and evaluation of novel light-curing dental nanocomposite

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A novel light-curing dental nanocomposite was explored to improve the shrinkage and mechanical properties. Organic-inorganic hybrid nanoscale multifunctional POSS (polyhedral oligomeric silsesquioxane) was polymerized with composite resins to synthesize the new dental nanocomposite. The structure of POSS-containing networks was analyzed by FTIR, WAXD and DSC. Their properties were evaluated including shrinkage, strength, elastic modulus, hardness and toughness. Molecular dynamics simulations were performed to study the effects of POSS with different loading levels on the properties of a model nanocomposite. Calculated volume- temperature behavior and X-ray scattering profiles were compared with experimental results. The shrinkage of nanocomposite polymerized with POSS was showed to be improved remarkably, declined from 3.53% to 2.18% at most. The mechanical properties of novel nanocomposite were greatly increased, for example, with only 2wt% POSS added, the nanocompsite's flexural strength increased 15%, compressive strength increased 12%, hardness increased 15% and uncommonly, even the toughness of resins was obviously increased(+56%). Cohesive energy density was calculated and found to be decreased with POSS copolymerized and chain packing around the POSS cluster was evaluated through radial distribution functions. The mobility of the POSS clusters was determined via the mean square displacement. The mechanical properties and shrinkage of light-curing dental nanocomposites polymerized with POSS can be improved significantly. And their wear resistance and service life were also increased greatly. The simulated results implied that new nanocomposite system formed a netlike distribution which may form a structural network holding the composite together and resulting in increasing mechanical properties.

7646-36, Session 11

Versatile smart optical material characterizer

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A versatile Smart Optical Material (SOM) characterization system is constructed based on Michelson interferometer system. SOM characterization system can measure not only the intensity of light through materials but also deep properties of light such as phase angle, polarization dependence, coherence, and so on. It can characterize electro-optic materials including liquid crystal, non-linear optical crystal, and electro-optic polymer, magneto-optic materials with Faraday effect and Kerr effect, motion of MEMS devices, thermal expansion coefficients, optical property changes by chemical reaction and concentration, stress and strain coefficient, piezoelectric coefficient, electro-chromism, and so on. Advanced software can characterize not only one-point measurement, but also multi-pixel measurement for array type devices as well. SOM characterization system supports development of versatile optical materials and devices for adaptive optics system, optical fiber communication, optical display, and optical data storage system.

7646-37, Session 11

Bioelectronic photosensing array for non-planar imaging

G. K. Knopf, The Univ. of Western Ontario (Canada)

Omni-directional and wide field-of-view imaging systems require complex optical assemblies to project time-varying spatial information onto the flat surface of a CCD or CMOS sensor array. These optical systems are often prone to geometric distortions, alignment errors, vibrations, and thereby difficult to calibrate for field applications. Biological vision systems, in contrast, use simple optics and numerous highly-sensitive photoreceptors distributed in non planar arrays. A novel imaging system that exploits the photoelectric signals generated by dried bacteriorhodopsin (bR) films is described in this paper. The dry bR thin film deposited on the microelectrodes respond to light intensities over a wide dynamic range (ten orders of magnitude) and exhibit a quantum efficiency of nearly 64%. By fabricating patterned sensor arrays on flexible plastic substrates it is possible to develop non planar imaging surfaces (eg. cylinder, sphere). In addition, the spatial pattern and size of individual pixels can be modified prior to printing the conductive electrodes on the PET plastic sheet. The flexible and lightweight photosensor array is manufactured on an indium-tin-oxide (ITO) coated plastic film using electrophoretic sedimentation (EPS). Each sensor pixel is 1mmx1mm and arranged in a 16x16 array. Experiments show that the peak spectral response occurs at 568nm and is linear over the tested light power range of 200uW to 12mW. The

photosensor response remains linear at the other tested wavelengths but the amplitude is reduced. A bendable microlens assembly, with discrete glass lenses, is used to focus the light onto the individual elements. Suggestions for improvement are presented.

7646-38, Session 11

Can magnetotactic bacteria in multiple optical traps be used to form magnetic nanostructures?

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Magnetic bacteria have attracted attention for their ability to grow single domain cuboctahedral iron oxide nanoparticles that can help to align multiwalled carbon nanotubes during growth. This paper describes a first experiment with helical, magnetic bacteria in optical tweezers. Magnetosprillum Magnetotacticum cells, 4 to 5µm in length with a diameter of 0.5µm were placed in solution, sealed between microscope slides and placed in the focus of optical tweezers. Since M. Magnetotacticum has a helical shape, it rotates when held in optical tweezers due to the momentum transfer from the tweezing light. Measurement of various M. Magnetotactica's rotational speeds with respect to photon flux showed linear results with speeds (1 to 13Hz) comparable to small birefringent valerite crystals (diameter 5 to 7µm), which are driven by spin angular momentum transfer from light [1]. Rotating bacteria could thus have a similar microfluidic flow of 200 µm3s-1 . It can thus be used as a micromotor for microfluidic flow applications. We suggest using multiple traps to create a defined array of M. magnetotacticum. In order to preorient the bacteria and their dipole moments, a homogenous magnetic field can be applied. Several line foci can then drag and orient the bacteria and their nanometer wide dipoles into the required position.

[1] J. Leach, H. Mushfique, R. di Leonardo, M. Padgett, J. Cooper, Lab Chip, 6, 735-739 (2006)

7646-39, Session 12

Flexible PEDOT:PSS strain gauge

W. Wang, Univ. of Washington (United States)

Organic electronics have emerged as an important technology in the near future. The applications of it are being intensively studied such as flexible display, electric label and organic energy harvesting device. The developments of these organic devices create a trend to shift the traditional hard material to soft material. Thus the term-soft electronics was created to describe the organic electronics. It is apparent that the flexible conducting material plays a vital role in the development of the organics device since the crack will be generated in common metal such as silver or gold when cycling load is applied. Among all the conducting polymer, poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) abbreviated as PEDOT:PSS are known for its high conductivity and processability because it can be dissolved in water with low viscosity which is suitable for low cost inkjet printing process. In this case, the mechanical property characterization of PEDOT:PSS becomes important due its reliability issue when subjected to cycling load. Recently, research shows that the stress and strain curve of PEDOT:PSS highly depends on the environmental humidity which reveal the instability issue of PEDOT:PSS when it is used as an component or a sensor. Furthermore, the way of PSS distributed in PEDOT structure will also affect the resistivity of the bulk material especially when external polar solution is added into PEDOT:PSS.

In this paper, we present a reliability test of PEDOT:PSS conducting polymer strain gauge to measure the bending motion of the rectangular plate. Compare to commercial available strain gauge, the flexible and piezo-resistive PEDOT: PSS strain gauge has benefit to measure larger deformation without damaging itself. In our experiment, PEDOT:PSS strain gauge is first made by molding PEDOT:PSS(Baytron P, German) on Polyurethane(Bond Polymer, USA) and, then attach to the rectangular acrylic plate. The sensor are further tested by 3-points bending test system to monitor the strain and resistance. Using resistance as an index of the internal structure change, the reliability of PEDOT:PSS can be revealed. The test system consists of force gauge, linear stage and multi meter to measure the strain and resistance change. Material testing system is controlled by National instrument (NI) and Labview program.

7646-40, Session 12

Organic electronics based pressure sensor towards intracranial pressure monitoring

P. Rai, V. K. Varadan, Univ. of Arkansas (United States)

The intra-cranial space, which houses the brain, contains cerebrospinal fluid (CSF) that acts as a fluid suspension medium for the brain. The CSF is always in circulation, is secreted in the cranium and is drained out through ducts called epidural veins. The venous drainage system has inherent resistance to the flow. Pressure is developed inside the cranium, which is similar to a rigid compartment. Normally a pressure of 5-15 mm Hg, in excess of atmospheric pressure, is observed at different locations in side the cranium. Increase in Intra-Cranial Pressure (ICP) can be caused by change in CSF volume caused by cerebral tumors, meningitis, by edema of a head injury or diseases related to cerebral atrophy. Hence, efficient ways of monitoring ICP need to be developed. A sensor system and monitoring scheme has been discussed here. The system architecture consists of a membrane less piezoelectric pressure sensitive element, organic thin film transistor (OTFT) based signal transduction, and signal telemetry. The components were fabricated on flexible substrate and have been assembled using flip-chip packaging technology. Material science and fabrication processes, subjective to the device performance, have been discussed. Capability of the device in detecting pressure variation, within the ICP pressure range, is investigated and applicability of measurement scheme to medical conditions has been argued for.

7646-41, Session 12

A bio-inspired flow sensor

X. Yu, Case Western Reserve Univ. (United States)

Accurate measurement of the turbulent flow is an important step to understand the mechanisms of many unknown phenomena. The turbulent flow generally can not be easily measured without significantly disturbing the original flow conditions. This paper introduces the efforts to develop a bio-inspired sensor for monitoring the turbulent flow. The sensor consists of an array of micro-pillar or nano-pillar. It looks into the fluid sensing capability of carbon nanotube bundles and its potential as the key sensing elements in the construction of micro-pillar. The performance was evaluate for its sensitivity as turbulence flow sensor.

7646-42, Session 12

Smart textiles with nanosensor array for point-of-care soldier health monitoring in real time

V. K. Varadan, Univ. of Arkansas (United States)

A new paradigm in healthcare, driven by cost and quality issues, is now emerging, which enables continuous point-of-care (POC) monitoring of soldier's vital signs such as heart rate (ECG), respiration, body temperature, galvanic skin response (GSR), and motion activities (EMG) and sensing and monitoring of chemical and biological threats and improve the survivability of soldiers in battlefields. The proposed architecture is also useful for monitoring and control of neurological and cardiovascular disorders for civilians at home. Real-time health monitoring could ensure the effectiveness of therapy by providing prevention, and early risk detection, which will significantly reduce healthcare costs by avoiding unnecessary hospitalizations. Latest advances in organic electronics have the ability to realize light and

cost-effective smart fabrics with embedded electronics and sensors combined with wireless communications. In this presentation, we introduce several organic based sensor devices capable of measuring temperature, strain, ph and potassium ion concentrations, each of which will enable us to monitor the patient's respiration rate, skin/body temperature, and the onset of Acute Myocardial Ischemia and neurological disorder triggered by chemical and biological species. It is expected that these flexible organic sensors can easily fit on garment with wireless instrument, and this sensory suit will be ideal for the real-time monitoring of vital kinematics and signs at remote locations for activity and location monitoring. Selected movies illustrating the applications of both invasive and non-invasive wireless sensor systems to patients and surgical procedures will be shown at the talk.

7646-43, Session 13

Wave propagation and structural dynamics in graphene nanoribbons

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Graphene nanoribbons (GNRs) are novel interesting nanostructures for the electronics industry, whereas their state as metallic or semiconductor material depends on the chirality of the graphene structure. We model the natural frequencies and the wave propagation characteristics of GNRs using an equivalent atomistic-continuum FE model previously developed by some of the Authors, where the C-C bonds thickness and average equilibrium length during dynamic loading are identified during a nonlinear minimisation process of the system Hamiltonian. We demonstrate that the thickness and equilibrium lengths for the different dynamic cases are different from the classical constant values used in open literature (0.34 nm for thickness and 0.142 nm for equilibrium length), in particular when considering out-of-plane flexural deformations. These parameters have to be taken into account when nanoribbons are designed as nano-oscillators.

7646-44, Session 13

Effect of thickness on characteristics of ZnO thin films prepared by sol-gel process

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Among oxide semiconductors, ZnO is a subjected to numerous extensive studies due to its potential applications in the field of electronics, optoelectronics and information technology devices including displays, solar cells and sensors. ZnO is a wide band gap semiconductor (3.37 eV) and high excitation binding energy of 60 meV with unique properties including transparency in the visible range and high infrared reflectivity, acoustic characteristics, piezoelectricity, and excellent chemical and physical stability. We present our results of characterization of ZnO thin films fabricated with sol-gel methods. Thickness of the sol-gel based ZnO film was controlled by a multiple coating process. Crystallization by annealing was performed over the range at 750o C. The effects of thickness on the surface morphology, microstructure and optical properties of the films were investigated. The film thickness increased as the coating time increased. From the XRD study, it is observed that the ZnO films with varying thickness demonstrated wurtzite structure (002) and as the thickness increased the intensity of (002) peak also amplified. Transmittance of the prepared solution increased upon 24 h of aging, which might be due to formation and gradual growth of crystals in the solution. Effect of thickness on Schottky behavior was evaluated by current-voltage characteristics, the undoped ZnO thin films with thickness of 132 nm exhibited perfect Schottky characteristics with high rectification ratio.

7646-45, Session 13

Characterization of micro-scale surface features using partial differential equations

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Micro-injection moulding (micromoulding) is an emerging technology useful for mass production of devices and components with micro and nano scale surface features and a complex three-dimensional surface geometry for a range of applications including micro-optics, couplings and life science applications. The process can be sensitive to changes in processing variables such as the flow properties of raw materials and machine fluctuations so it is therefore useful to employ Quality Assurance techniques into the production cell to verify product quality of each product following manufacture. Such systems are usually required to perform three-dimensional measurements of surface structures, and to this end, a range of techniques can be adopted including Extended Depth of Field (EDOF) and White Light Interferometry (WLI). However, such techniques generate measurement datasets as regular Cartesian cloud point data which can be large and unwieldy, particularly for large, high resolution scans and there is a clear need for compression of the data required by picking out key geometric feature properties which can be used as product quality indicators. Therefore, the problem remains to represent the surfaces thus generated, associated with large data sets, in an efficient way that will facilitate their analysis and characterization.

The technique proposed here is based on the use of Partial Differential Equations (PDEs) to describe the outer shell of the resulting surface profiles from the raw measurement data. This technique has been developed with the aim of identifying a number of parameters responsible for determining the surface profile of a given product. This set of parameters can then be compared with the theoretical values associated with a particular surface profile (essentially the mathematical functions which describe the mould cavity surface) and therefore determine the quality of the produced parts by studying the error between the two parameter sets. Ideally, a moulded product should follow the form of the mould from which it was produced exactly, therefore the error calculation provides a direct measurement of the moulding deficiency.

Experimentally, the measurement data corresponding to the manufactured pieces is obtained through WLI (Wyko NT1100 off-line instrument and an in-process system designed and assembled at the University). Such data is thus processed so that the cloud point data is reduced to a set of boundary curves (reducing memory requirements) and then, a PDE surface is computed which can be compared against the ideal profile. Differences between the theoretical (mould) and measured (product) surfaces can be evaluated against calculated criteria such as height, surface area and volume. Moreover, a criterion based on the coefficients associated with the analytic solution of a given mould can be employed to implement quality assessments of the manufactured components with low solution times, allowing such systems to be easily integrated into the production process. Additionally, this surface generation technique provides an analytic expression for such a surface over a two-dimensional parametric space, which could potentially facilitate the numerical solution of a given mathematical model involving any of the physical properties associated with the micromoulding process.

7646-46, Session 13

SERS from ellipsoidal nanoparticles

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The mathematical formulation to determine enhancement factors of Raman scattered light from molecules adsorbed on spherical and spheroidal particles has been previously studied. But many applications require that the particle on which a Raman active molecule is adsorbed is not one of these simple shapes or the application might even require the particle to be coated. In this paper we extend the established mathematical technique to derive enhancement from molecules adsorbed on an ellipsoidal particle having in general any number of

coatings of other substances on it. We then use our formulae to study enhancement of Raman scattering from molecules like pyridine and CV from nanoparticles of gold and silver as well as their core-shell structures with magnetic metal cobalt. The nanoparticles of these metals are widely used in biomedical applications. We also present results for the cases when the nanoparticle is covered with a monolayer of Raman active molecules and dispersed randomly in a medium. Our results can be of vital importance in medical technology.

7646-47, Session 13

Mathematical modeling for the design of porous coronary stents: nano- and microporous stents v. macroporous stents

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Drug delivery polymers play a role in late in-stent thrombosis of first generation drug-eluting stents (DES) via an inflammatory reaction. To circumvent this problem, subsequent generation DES have non-polymer based DES whose surface pores serves as a drug reservoir. While drug elution for pores in the nanometer range have been shown to be comparable to polymer-based DES in terms of intimal suppression, how different pore sizes effect drug elution has not been fully characterized. We hypothesized that drug elution can be characterized with a mathematical model that takes into account the pore size of the stents and molecular characteristics of the eluted drug. Methods: Structural data from six porous, non-polymer based stents were examined with pore size ranging from 5 nm to > 10 mm (1-Setagon Stent, Setagon Inc., Charlottesville, VA; 2-Yukon stent, Translumina GmbH, Hechingen, Germany; 3-ESI Microporous Stent, ESI Inc, Stillwell, KS; 4-Synergy Biomatrix, Medlogics Device Corporation, Santa Rosa, CA; 5, 6- CoStar and Conor Stents, Cordis Medsystems, New Brunswick, NJ). All stents eluted either Tacrolimus or Sirolimus. We constructed a mathematical model based on mass transport of molecules through a porous media. A dimensionless number was derived characterizing molecular flux of the drugs through a porous membrane. Results: Figure. 1 demonstrates that there was exponential rise in molecular flux of the eluted drug with pore sizes greater than 5 micrometers. The molecular characteristics of the eluted drug did not affect the molecular flux. Conclusions: Stents in the nano- and microporous range will have similar drug elution profiles; while macroporous stents will vary greatly. Careful attention to pore size may significantly enhance the design and efficacy of microporous polymer free stents.

7646-48, Session 14

Comprehensive design and process flow configuration for micro and nano tech devices

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The development of micro and nano tech devices based on semiconductor manufacturing processes comprises the structural design as well as the definition of the manufacturing process flow. The approach is characterized by application specific fabrication flows, i.e. fabrication processes (built up by a large variety of process steps and materials) depending on the later product. Technological constraints have a great impact on the device design and vice-versa.

In the first part of this paper we introduce a comprehensive methodology for customer-oriented product engineering of MEMS products. Micro and nano tech product development tailored towards a distributed, networked operation between customers, designers and semiconductor manufacturing partners are in the focus of this methodology. The micro and nano device engineering process is analyzed with regard to different business cases (e.g. IDM, fables design houses etc.) taking into account application-specific procedures and (data) interfaces. The results are used to develop and to enable an appropriate CAD support either by incorporating existing CAD tools or by specifying individual tools to be implemented.

Pars pro toto we introduce subsequently an environment for the development of new processes to manufacture micro and nano devices. The environment provides central data management for manufacturing knowledge, handling the whole range of process related information and their complex relationships. Specific tools supporting the process management and design tasks like consistency check of fabrication processes and process simulation have been implemented based on the data management.

The development is currently carried out in an international multi-site research project (CORONA - funded by the European Commission CP-FP 213969-2).

7646-49, Session 14

Smart energy management system

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Peak and average energy usage in domestic and industrial environments is growing exponentially and absence of detailed energy consumption metrics is making systematic reduction of energy usage very difficult. Smart Energy Management System aims at providing a cost-effective solution for managing soaring energy consumption and its impact on green house gas emissions and climate change.

The solution is based on seamless integration of existing wired and wireless communication technologies combined with smart context-aware software which offers a complete solution for automation of energy measurement and device control. The system can communicate over existing power lines thereby allowing a low cost retro-fit model for existing devices/appliances. The persuasive software presents users with easy-to-assimilate visual cues identifying problem areas and time periods and encourages a behavioural change to conserve energy.

The system allows analysis of real-time/statistical consumption data with the ability to drill down into detailed analysis of power consumption, CO2 emissions and cost. The system generates intelligent projections and suggests potential methods (e.g. reducing standby, tuning heating/cooling temperature, etc.) of reducing energy consumption. The user interface is accessible using web enabled devices such as PDAs, PCs, etc. or using SMS, email, and instant messaging.

Successful real-world trial of the system has demonstrated the potential to save 20 to 30% energy consumption on an average. Low cost of deployment and the ability to easily manage consumption from various web enabled devices offers gives this system a high penetration and impact capability offering a sustainable solution to act on climate change today.

7646-50, Session 14

Implementation of capacitive RF MEMS switches into a monolithic GaN on silicon microwave technology

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The use of micro-machined switches for RF switching applications was first demonstrated in 1979 . Since then, a large amount of research effort has focused on the fabrication and the implementation of micro-machined switches for various applications and specifications such as reflect array antennas or phase shifters. Despite the differences in designs, these switches have demonstrated the low insertion loss, high isolation and low return loss (good impedance matching) at microwave frequencies. Wide Band-Gap (WBG) Semiconductors are being developed to replace GaAs based technologies. Some devices has already reached specifications for applications .reports the measured S-parameters in the 0-40 GHz frequency range, for the UP state and DOWN state of the switch. For 40 GHz switching operation, when the switch is in the UP state, the insertion loss (a) of the switch is 0.3 dB with the return loss (b) better than 11 dB; when the switch is switched to the DOWN state, the isolation (c) is 28 dB. The pull-down voltage ranges from 30 to 40 volts. (see geometrical Parameters and microwawe characteristics of TRT shunt switch in Table1). The

measurement of RF MEMS switches have been done at Thales Research and Technology. If we want to join these capabilities, it is a tricky point to show that GaN substrates present the same microwaves losses as high-resistivity silicon substrate or Glass. Simulations and measurements demonstrate RF-MEMS Switches on GaN on Silicon substrate with metallic membrane possess low insertion loss and good isolation at frequencies up into the millimeter-wave bands. A further task will be devoted to the design, test specific fabrication and RF characterisation of a Single Pole Double Throw (SPDT) RF-MEMS switch and MMIC circuits for final demonstrator as active T/R module.

7646-51, Session 15

A very high Q-factor inductor using MEMS technology

N. Khalid, La Trobe Univ. (Australia)

Quality (Q) factor is an important characteristic of a inductor which significantly affects the performance of the radio frequency (RF) circuits and systems such as gain/noise figure of the low noise amplifier (LNA) and the phase noise of voltage controlled oscillator (VCO). Higher Q inductors help minimise RF power loss, RF noise, phase noise and DC power consumption of RF integrated circuits. High Q inductor design and fabrication remain a challenge for designers to design components that depend on passive components performance such as low phase-noise VCO, power amplifier (PA), LNA and mixers. The Q factor and frequency limitations still limit RF front-end circuitry to a large number of discrete passive components and make RF front-end module integration very critical.

Currently, MEMS is actively being investigated and developed for high performance RF circuits. MEMS is an enabling technology and can replace most of the components in a receiver for RF applications. RF MEMS technology enables the realisation of small communication device elements or modules with high performance, lower insertion loss, higher isolation, and better linearity than semiconductor devices that are currently used.

7646-52, Session 15

Annealing temperature effect of GaN thin layer Schottky diodes

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GaN is a wide band gap semiconductor, approximately 3.4 eV, and has been widely used in various application fields including blue and ultraviolet light emitting diodes, Schottky diodes, and other electronic devices. For these applications, various techniques have been employed, such as metal-organic chemical vapor deposition, molecular beam epitaxy, vapor phase epitaxy, pulsed laser deposition, and chemical solution deposition. Among these techniques, chemical solution deposition has superior advantages due to the no requirement of expensive equipments, no management cost for the expensive equipments, wide area applications, doping capability, thermal stability, and potential integration and used in this study. Ga(NO3)3 (0.3 g) has been dispersed in ethanol (5 g). Acetic acid (3 ml) was added and stirred for 24 h. Resulting solution was spin-coated onto a Si substrate with spinning rate of 1000 rpm for 10 sec. Coated Si wafer was heated in hotplate at 200 °C for 10min and these processes were repeated three times. These resulting Ga2O3 layers annealed in tube furnace with constant flow of NH3 gas at high temperature such as 700, 800, 900 °C. These films were investigated with x-ray diffractograms. To investigate Schottky characteristics of the converted GaN layer, Al electrode was deposited on top of the GaN layer, and current-voltage characteristics were investigated.

7646-53, Session 15

Thermal indicating paints for ammunition health monitoring

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Ammunition is often exposed to extreme temperatures and solar radiation during transport and storage. This is of particular concern in the present theater of operations. It was documented during Desert Storm operations that temperatures inside munitions' containers exceeded 190oF degrees. This significantly exceeds the design limits of 145oF - 165oF. Currently there is no way to know what environmental extremes fielded items have experienced. An easily readable indication of the environmental exposure history of an item will enable troops and munitions managers to readily identify ordnances that may have been compromised. Furthermore, compromised munitions can be screened out to ensure mission success and enhancing soldier safety. Thermal chromic polymers that change color in response to external stimuli are being tailored to paints and coatings to alert Army logistic staff of dangerous temperature exposures. Irreversible indication via color change in multiple thermal bands, 145oF-164oF, 165oF-184oF and over 185oF, are possible with these thermal polymers. The resulting active coating can be visually inspected to determine if safe temperatures were exceeded. The coatings are comprised of cost-effective and commercially available monomers of conjugated polymer diacetylenes. The conjugated polymeric backbone of polydiacetylenes (PDAs), undergo intriguing stress-, chemical- or temperature-induced chromatic phase transitions associated with the disruption of the backbone structure and shortening of the conjugation length. PDAs, such as 10, 12 pentacosadiynoic acids (PCDA), form nanocomposites and uniform blends with polymers. Cumulative time of exposure in multiple temperature bands can be sensed and optically detected by mixing small amounts of time-temperature sensitive diacetylene monomers into coatings.

7646-54, Session 15

Fabrication of UV-micro-patternable permanent micro magnets for lab on a chip and MEMS

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High quality permanent magnet materials are pivotal for development of magnetic microsystems such as microscale sensors, micromotors, actuators and power generators. One of the biggest advantages of permanent micromagnets is that they can generate high forces over comparatively long working distances, which is attractive for, among other things, manipulation of fluids in micro total analysis systems that require actuation to facilitate fluid transport and mixing. In this paper we present fabrication of UV patternable permanent micromagnets which are capable of generating large bi-directional forces with long working lengths. We present UV patterned permanent micromagnets fabricated at Micro-Instrumentation Lab (Simon Fraser University, Canada) by ultrasonic agitation MQP- Spowder (manufactured by Magnequench International Inc) in SU-8 which is a negative tone photoresist. This powder is composed of spherical particles which have a typical median size of 50 µm. It has a remanent induction (Br) of 0.75 T , a theoretical density of 7.43 g/cm3 and an apparent density of 4.2 g/cm3. It is an NdFeB based isotropic powder manufactured by Magnequench Inc. The resulting composite was successfully UV patterened down to the size of 500 µm x 300 µm with a height of 200 µm. The fabricated micromagnets were magnetized with an electromagnetic charger and tested using a Tesla meter and found to have a magnetic field intensity of 0.7mT at the surface of the magnet.

7646-55, Session 15

Nanowire-organic thin film transistor integration and scale up towards developing sensor array for biomedical sensing applications

P. S. Kumar, P. T. Hankins, P. Rai, V. K. Varadan, Univ. of Arkansas (United States)

Exploratory research works have demonstrated the capability of conducting nanowire arrays in enhancing the sensitivity and selectivity of bio-electrodes in sensing applications. With the help of different surface manipulation techniques, a wide range of biomolecules have been successfully immobilized on these nanowires. Flexible organic electronics, thin film transistor (TFT) fabricated on flexible substrate, was a breakthrough that enabled development of logic circuits on flexible substrate. In many health monitoring scenarios, a series of biomarkers, physical properties and vital signals need to be observed. Since the nano-bio-electrodes are capable of measuring all or most of them, it has been aptly suggested that a series of electrode (array) on single substrate shall be an excellent point of care tool. This requires an efficient control system for signal acquisition and telemetry. An array of flexible TFTs has been designed that acts as active matrix for controlled switching of or scanning by the sensor array. This array is a scale up of the flexible organic TFT that has been fabricated and rigorously tested in previous studies. The integration of nanowire electrodes to the organic electronics was approached by growing nanowires on the same substrate as TFTs and flip chip packaging, where the nanowires and TFTs are made on separate substrates. As a proof of concept, its application has been explored in various multi-focal biomedical sensing applications, such as neural probes for monitoring neurite growth, dopamine, and neuron activity; myocardial ischemia for spatial monitoring of myocardium; and field applications for detecting food pathogens and gases.

7646-56, Session 15

Magnetic nanocomposites for drug delivery with controlled release

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In a typical targeted drug delivery, carriers transport and release drugs to a target site, and it is highly desirable to eliminate undesirable drug release before reaching the target site. Traditional stimuli, such as electric signals, ultrasound and acidity, often require a physical or chemical contact with the drug carriers to trigger the release. However, triggering a drug release in such a manner is usually not practicable in the human body.

We will report our work on the development of magnetic nanocomposites that can be used as carriers for drug delivery with controlled release. The magnetic nanocomposites we developed mainly consist of magnetic nanomaterials and heat-responsive polymers. The magnetic nanomaterials can be addressed and stimulated by external magnetic fields in a noncontact and remote nature, and the heat-responsive polymers are used as the host media. Such magnetic nanocomposites are dual-responsive: the magnetic nanomaterials respond to the external magnetic fields, and the polymers respond to the heat produced by the magnetic nanomaterials. Due to this dual-response characteristic, the drugs loaded in the magnetic nanocomposites will be released in a way controlled by external magnetic fields: magnetic fields cause heat-responsive polymer to shrink, squeezing drugs out from the nanocomposites.

The self-recovery capability of nanocomposites is essential for programmable drug release. Our work will concentrate on the development of magnetic nanocomposite carriers with self-recovery capability: after a burst-like drug release, the carriers can adjust their structures, and the remaining drugs in the carriers can continue to be released in a controllable way.

Conf. 7647: Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems

Monday-Thursday 8-11 March 2010

Part of Proceedings of SPIE Vol. 7647 Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2010

*** Indicates papers that will also be presented in the NSF Poster Session**

7647-03, Session 2a

Feasibility of embedded wireless sensors for monitoring of concrete curing and structural health

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When designing civil structures the objective is to design a cost effective, reliable and durable structure. Many old structures are now reaching the limit of their design life and are being replaced with “smart” structures. These structures are self-monitoring and have the ability to predict failure allowing steps to be taken to mitigate the affects and in many cases save lives.

The aim of this project is to design a sensor which monitors the concrete structure during the two stages of its life - the curing stage and its subsequent service life. Monitoring the curing process of concrete will ensure a durable structure is constructed while monitoring of structural health will determine how the structure is performing.

A key research challenge for such a sensor is to determine if it is feasible to embed wireless technologies within concrete. The composition of concrete, with different sized aggregates and steel reinforcement bars may have a significant affect on the attenuation of electromagnetic waves from deep within the concrete and seriously affect the functionality of wireless sensors. The sensor must also withstand the aggressive environment within the concrete. Initial tests were designed to determine the affects of reinforcement bars and large aggregates had on data transmission. The subsequent design and packaging of a prototype wireless sensor to monitor the two main parameters which ensure concrete is curing completely - internal relative humidity and temperature - is described along with the response of the sensors when embedded in concrete over a time period of 60 days.

7647-04, Session 2a

The Smartbrick wireless sensor node for high-resolution structural health monitoring

B. O. Banks, D. A. Lecko, S. Sedigh, Missouri Univ. of Science and Technology (United States)

This paper introduces a wireless sensor node for the SmartBrick platform, which provides a low-cost and autonomous method for structural health monitoring. Design and testing of the SmartBrick base station have been described in previous publications. The SmartBrick sensor node presented in this paper leverages the Zigbee short-range communication capabilities of the base station to increase the monitoring range of the system. The primary function of the node is to interface to humidity, temperature, tilt, strain, and vibration sensors and transmit their values to the base station via Zigbee. The GSM modem included in the base station has been omitted from the sensor node, in order to reduce cost, form factor, and power consumption. Long-range communication of data and alerts will be through the base station, which serves as the gateway to the outside world, and relays remote configuration and maintenance commands to the sensor nodes.

One of the primary motivations behind development of the sensor node is high-resolution monitoring of strain. Each wireless sensor node will be able to measure strain from 16 different locations on a structure, by multiplexing these gauges to the same signal conditioning circuit, which drastically reduces the number of nodes required for monitoring an area. Data collection can take place at regular intervals, or when triggered by events of interest. Each sensor node includes sufficient memory to store a day’s data, although the system default is to transmit the collected data to the base station once per hour.

7647-05, Session 2a

Development of high-sensitivity sensor for structural health monitoring

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Structural Health Monitoring (SHM) system using smart sensors has been a hot issue recently. State-of-the-art smart sensor technology makes it possible to deploy dense array of sensors through a structure because of the benefit of its cost-effectiveness, easy installation and wireless communication so that a sensor network provides an abundance of structural information. However, relatively low resolution of MEMS sensors generally adopted in smart sensor puts a limitation on the application to low-level vibration such as ambient vibration of building structure. For extensive application of smart sensor network to diverse structures, the limitation should be eliminated, and accurate sensor should be available for the wireless smart sensor system. In this study, as the possible solution to the limitation, the development of high-sensitivity acceleration board for Imote2 platform is explored. For this sensorboard, a low-noise accelerometer (SD1221 of Silicon Designs Inc., capacitive sensor) is used, and several considerations are implemented to reduce the noise effects from diverse components including power source, resistors and ground plane. The capacity of the high-sensitivity accelerometer board is verified through various static and dynamic tests and compared with that of other MEMS sensors. The high-sensitivity sensor can be used to measure low-level ambient vibration and utilized as reference sensor to enhance the accuracy of other sensors.

7647-06, Session 2a

Structural health monitoring system of a cable-stayed bridge using a dense array of scalable smart sensor network

S. Cho, Korea Advanced Institute of Science and Technology (Korea, Republic of); S. A. Jang, H. Jo, K. Mechitov, Univ. of Illinois at Urbana-Champaign (United States); J. A. Rice, Texas Tech Univ. (United States); H. Jung, C. Yun, Korea Advanced Institute of Science and Technology (Korea, Republic of); B. F. Spencer, Jr., Univ. of Illinois at Urbana-Champaign (United States); T. Nagayama, The Univ. of Tokyo (Japan); J. Seo, Hyundai Motor Co. (Korea, Republic of)

This paper presents a structural health monitoring (SHM) system using a dense array of scalable smart wireless sensor network on a cable-stayed bridge (Jindo Bridge) in Korea. The components of the SHM system are Crossbow’s Imote2s, custom-designed multi-scale sensor boards, base station computers, and Illinois Toolsuite for SHM application. 70 sensors and two base station computers have been deployed to monitor the bridge using an autonomous SHM application with threshold exceeding events induced by wind and vibration. For the deployment in situ for long-term monitoring, communication parameters for the wireless sensor network have been optimized considering the characteristics of the bridge and the communication range of the sensors. The performance of the system has been evaluated in terms of hardware durability, software stability, and power consumption. 3-D modal properties were extracted from the measured 3-axis vibration data using output-only modal identification methods. Tension forces of 4 different lengths of stay-cables were derived from the ambient vibration data on the cables. For the integrity assessment of the structure, multi-scale subspace system identification method is

now under development using a neural network technique based on the local mode shapes and the cable tensions.

7647-07, Session 2a

Issues of signal strength of wireless sensors for civil infrastructure monitoring

L. S. Bryson, T. J. Lutz, A. Barnes, Univ. of Kentucky (United States)

Research was conducted using simulated civil infrastructure system conditions to evaluate issues pertaining to signal strength. This research evaluated the performance of the wireless MICA2 sensor motes developed by Crossbow Technology, Inc. The data collected is intended to demonstrate how the motes would perform in a typical civil infrastructure application when placed in a large network of sensors. Specific to signal strength, the strength, quality, and reliability of the signal originating from remote sensor was assessed as a function of its distance from the Gateway Sensor. These experiments encompassed several factors that relate to signal strength and distance such as single motes, multiple motes, single hop, and multi-hop. Experimentation was also performed to evaluate the mote performance for buried applications. The results of the experimentation show that in all cases the quality, reliability and strength of the transmitting signal is a function the distance of the Gateway Sensor from the obstruction and the amount of signal scattering caused by the material surrounding the mote.

7647-08, Session 2b

An experimental study on AEKF method for damage detection of base-isolated structures

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An objective of a structural health monitoring system is to identify the state of the structure and to detect the damage when it occurs. In this regard, analysis techniques for damage identification of structures, based on vibration data measured from sensors, have received considerable attention. Various approaches for system identification and damage detection have been proposed in the literature, including literature reviews and structural health monitoring (SHM) benchmark problems. When a structural element is damaged, such as cracking, the stiffness of the damaged element is reduced. Hence, the structural damage may be reflected by the changes of parametric values of the damaged element. During a severe dynamic event, such as a strong earthquake, a structure may be damaged, and the damage events or the reductions of the stiffness of damaged elements will be contained in measured vibration data. To identify the structural damages using vibration data that contain damage events, system identification techniques in time domain have been developed for nonlinear and/or multi-degree-of freedom (MDOF) structural systems. On the other hand, many civil engineering structures exhibit hysteretic behavior when subject to severe dynamic loads, such as strong earthquakes and sea waves. Hence, the modeling and identification of nonlinear hysteretic systems are important for the damage detection of structures. Recently, a new adaptive tracking technique, based on the extended Kalman filter approach, has been proposed for the damage identification and tracking of structures. Simulation and experimental studies for linear structures have demonstrated that the adaptive extended Kalman filter (AEKF) approach is capable of tracking the variations of structural parameters, such as the degradation of stiffness, due to damages.

In this paper, an experimental study is conducted and presented to verify the capability of the adaptive extended Kalman filter (AEKF) approach for identifying and tracking the damages in nonlinear structures. A base-isolated building model, consisting of a scaled shear-beam type building model mounted on a rubber-bearing isolation system, has been tested experimentally in the laboratory. The non-linear behavior of the base isolators is modeled by the Bouc-Wen model. To simulate the structural damages during the test, an innovative device, referred to as the stiffness element device (SED), is proposed to reduce the stiffness of either the upper story of the structure or the base isolator. Two earthquake excitations have been used to drive the test model, including the El Centro and Kobe earthquakes. Various damage scenarios have been simulated and tested. Measured acceleration response data and the AEKF approach are used to track the variation of the stiffness during the test. The tracking results for the stiffness variations correlate well with that of the referenced values. It is concluded that the AEKF approach is capable of tracking the variation of structural parameters leading to the detection of structural damages.

7647-09, Session 2b

Applications of a structural damage detection method to experimental results

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An objective of structural health monitoring systems is to identify the state of the structure and to detect the damage when it occurs. Analysis techniques for damage identification of struc-tures, based on vibration data measured from sensors, have received considerable attention. Re-cently, new time-domain damage tracking approaches have been proposed in the literature; how-ever, little experimental tests were conducted for the verification purposes. To detect the local structural damages quantitatively, such as the degradation of the stiffness of an element, a finite-element formulation is required, which results in a large number of degree-of-freedoms (DOFs) system and thus requires a large number of sensor measurements. For practical applications, it is highly desirable to install as few vibration sensors as possible. Likewise, some vibration quanti-ties are difficult to measure, such as the rotational acceleration at a nodal point. To reduce the re-quired number of sensors, a method of reduced order system for the finite-element formulation is presented. In this paper, the adaptive damage tracking technique for structures recently proposed, referred to as the adaptive quadratic sum-square error (AQSSE), and a reduced-order finite-element approach are used to identify the local damages of structures. Experimental tests were conducted to verify the capability of the proposed approach. A series of experimental tests were performed using a scaled cantilever beams subject to different types of excitations, including the white noise and sinusoidal excitations. Based on the measured vertical acceleration data (without rotational response measurements) using only a limited number of sensors, the stiffness for all elements of the beam were identified. It is demonstrated experimentally that: (i) the proposed fi-nite-element based adaptive quadratic sum-square error approach is capable of detecting the structural damages using only a limited number of sensors, and (ii) the identification results for the stiffness of all finite-elements of the beam are quite accurate.

7647-10, Session 2b

Coupling coefficient analysis in damage detection using magnetic impedance approach

X. Wang, J. Tang, Univ. of Connecticut (United States)

Impedance method has been explored for damage detection and identification. Since the impedance information may be measured at relatively high frequency range, it has been recognized that the impedance method is sensitive to small-sized damage. Recently, the magnetic transducer is introduced into the impedance approach. Since it can be hung above the mechanical structure and move in the horizontal plane, the magnetic transducer based impedance approach may have many potential applications in online health monitoring systems for structure with complex geometry. One

important implementation issue is the weak magneto-mechanical coupling between the transducer and the structure. Compared with the impedance approach using piezoelectric transducer, the magnetic impedance approach may be less sensitive to the damage induced change of structural properties. In order to provide guidelines for enhancing the coupling between the magnetic transducer and the structure, the analytical model of magneto-mechanical coupling coefficient is formulated in this research. Based on this model, it is found that the coupling coefficient is closely related to the design parameters of the transducer, such as the voltage excitation frequency and the distance between the transducer and the top surface of the structure, etc. The correlated numerical and experimental studies are used to validate the modeling and analysis of coupling coefficient in magnetic impedance approach.

7647-11, Session 2b

Delamination detection using embedded BOCDA optical fiber sensor

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Delamination is the most critical damage of the carbon fiber reinforced plastics (CFRP), because such damages reduce its strength and stiffness. In the aircraft structures, detecting such damage during operation is very important issue. On the other hand, optical fiber sensing technology has developed significantly. Especially, the Brillouin optical correlation domain analysis (BOCDA) technology has been enhanced its measuring capability. The BOCDA technology has the unique characteristics; these are fully distributed strain measuring, and dynamic strain measuring at arbitrary points along the optical fiber sensor with high spatial resolution.

In these surroundings, we conducted the feasibility study to detect the delamination using the BOCDA measuring system. Firstly, we selected the optical fiber sensor type to fit embedding into composite structures. Embedding optical fiber sensor into CFRP structure causes transmission loss of the optical fiber sensor increase, and has a critical impact on the BOCDA measuring. So, we choose a low bending loss optical fiber as sensor for the BOCDA method, i.e. hole-assist fiber and high-delta optical fiber. These low bending loss optical fibers are low influence than normal optical fiber (such as telecommunication fiber). Secondly, we induced the artificial delamination damages to CFRP plate. The BOCDA measuring data, strain distribution and/ or Brillouin gain spectrum (BGS) shape, changed with artificial delamination expanding. Therefore the BOCDA measuring system has the ability to detect delamination damage of the CFRP structures.

7647-12, Session 2b

Monitoring of fatigue crack growth using guided ultrasonic waves

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Varying loading conditions of aircraft structures result in stress concentration at fastener holes, where multi-layered components are connected, possibly leading to the development of fatigue cracks. Guided ultrasonic waves propagating along a structure allow in principle for the efficient non-destructive testing of large plate-like structures, such as aircraft wings. However, the sensitivity for the detection of small defects has to be ascertained. This contribution presents a study of the detection and monitoring of fatigue crack growth using low-frequency guided ultrasonic waves and higher frequency Rayleigh-like waves. Two types of structures were used, single layer aluminum tensile specimens, and multi-layered structures consisting of two adhesively bonded aluminium plate-strips. Fatigue experiments were carried out and the sensitivity of the guided wave modes to monitor fatigue crack growth at a fastener hole during cyclic loading was investigated. Fatigue crack growth was monitored optically and the changes in the ultrasonic signal caused by the crack development were quantified. It was shown that fatigue crack detection and monitoring using both the low frequency guided waves and higher frequency Rayleigh-like waves is possible. The sensitivity and repeatability of the measurements were ascertained, having the potential for fatigue crack growth monitoring at critical and difficult to access fastener locations from a stand-off distance. Good agreement was observed between the experimental results and predictions from full three-dimensional numerical simulations of the scattering of the ultrasonic wave at the fastener hole and crack. The robustness of the methodology for practical in-situ ultrasonic monitoring of fatigue crack growth was discussed.

7647-13, Session 3a

Embedded EMD algorithm within an FPGA-based design to classify nonlinear SDOF systems

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Compared with traditional microprocessor-based systems, fast growing field-programmable gate array (FPGA) technology offers a more powerful, efficient and flexible hardware platform. An FPGA and microprocessor (i.e., hardware and software) co-design is developed to classify three types of nonlinearities (including linear, hardening and softening) of a single-degree-of-freedom (SDOF) system subjected to free vibration. This significantly advances the team's previous work on using FPGAs for wireless structural health monitoring.

The classification is achieved by embedding two important algorithms - empirical mode decomposition (EMD) and backbone curve technique. With its implementation in both the FPGA and microprocessor, numerous design considerations to embed EMD are discussed. In particular, the implementation of cubic spline fitting and the encountered challenges using both hardware and software environments are discussed. The backbone curve technique is fully implemented within the FPGA hardware and used to extract instantaneous characteristics from the uniformly distributed data sets produced by the EMD algorithm as presented in a precious SPIE conference by the team. An off-the-shelf high-level abstraction tool along with the MATLAB/Simulink environment is utilized to manage the overall FPGA and microprocessor co-design.

Given the limited computational resources with an embedded system, we strive for a balance between the maximization of computational efficiency and minimization of resource utilization. The beauty of this study lies far beyond merely programming existing algorithms to hardware and software. Among others, extensive and intensive judgment is exercised involving experiences and insights with these algorithms, which renders processed instantaneous characteristics of the signals that are well-suited for wireless transmission.

7647-14, Session 3a

Development of a wireless artificial soil particle sensor for monitoring particle movement at soil-structure interfaces

B. Liea, K. J. Loh, Univ. of California, Davis (United States)

The load transfer and shaft capacities of civil infrastructure foundations (e.g., axially-loaded piles) depend on the soil-structure interface's shearing and frictional behaviors. However, cyclic loading can dramatically deteriorate the shaft resistance of these foundations to cause catastrophic structural failure. Unfortunately, the mechanics of soil-structure interactions and interface responses are yet to be fully understood. In addition, although numerous tethered sensing systems have been developed for gaining insight on properties of soil-structure interfaces, the cables required to supply power and communicate with sensors adversely affect the true soil-structure interaction behavior during experimental investigations. In this study, a passive wireless

sensor is proposed for measuring the absolute displacement of soils at soil-structure interfaces. Wireless communications and power transmission to the sensor is accomplished via electromagnetic coupling between a portable reader and sensor. Here, the portable reader is simply a coil antenna connected to an impedance analyzer, and the sensor circuitry comprises a resistor, inductor (i.e., coil antenna), and capacitor connected in series or parallel. The absolute displacement of the embedded sensor can be easily measured by correlating reader impedance changes with the reader-to-sensor's distances. By achieving wireless data acquisition and by designing the sensor to be of a small form factor that is packaged in an epoxy mold comparable to the size and shape of neighboring soil particles, the device can be embedded within soil environments without disrupting the interface response during cyclic loading. Preliminary experimental results that characterize the passive wireless sensor's absolute displacement measurement performance are presented.

7647-15, Session 3a

Development of smart sensing system for structural health monitoring

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The objective of this paper is to upgrade a wireless sensing unit which can meet the following requirements: 1) Improvement of system powering and analog signal processing 2) Enhancement of signal resolution and provide reliable wireless communication data, 3) Synchronization on collecting of distributed data, 4) Enhance capability for continuous long-term monitoring. Based on the prototype of the wireless sensing unit developed by Prof. Lynch at the Stanford University, the following upgrading steps are summarized:

1. Increasing the capacity of power and considering the powering of sensor,

2. Reduce system noise by using SMD passive elements and preventing the coupling digital and analog circuits,

3. Improve the ADC sampling resolution and accuracy with a higher resolution Analog-to-Digital Converter (ADC): a 24bits ADC with programmable gain amplifier.

4. Improve wireless communication by using the wireless radio 9XTend which supported with the router (Digi MESH) communication function using 900MHz frequency band.

Based on the upgrade wireless sensing unit, verification of the new wireless sensing unit was conducted from the ambient vibration survey of an arch dam. This new upgrade wireless sensing unit can provide more reliable data communication for continuous structural health monitoring. Incorporated with the modified stochastic subspace identification method the smart sensing system is developed.

7647-16, Session 3a

Development of a wireless power transmission system for guided wave generation and sensing via a laser

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Guided waves based nondestructive testing (NDT) techniques have attracted many researchers' attentions for structural health monitoring due to their relative long sensing range. These guided waves in a structure can be generated and sensed by a variety of techniques. This study proposes a new wireless scheme for PZT excitation and sensing, where power as well as measured data can be transmitted via laser. First, a generated waveform modulated by a laser is wirelessly transmitted to a photodiode connected to a PZT on the structures. Then, the photodiode converts the light into an electrical signal and excites the PZT and the structure. The reflected response signal received at the same PZT is re-converted into a laser, which is transmitted back to another photodiode located at the data acquisition unit for diagnosis. The feasibility of the proposed power and data transmission scheme has been experimentally demonstrated at a laboratory setup. Since there is no need for a power supply and a signal generator at the PZT transducer node, a self-sufficient PZT transducer unit can be realized with little additional electronic components.

7647-17, Session 3a

Sandwich-Imote2 for wireless sensor networks in bridge monitoring applications

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MIT Technology Review named wireless sensor networks consisting of integrated sensing/communication/control devices as one of the ten technologies that will change the world in the 21st century. Sandwich-node is a concept design to remedy the shortcomings of the previous generation of integrated sensing/communication/control devices that have been used for structural health monitoring applications. Based on the popular Imote2 wireless sensor platform, we design and build such sandwich nodes, each consisting of two control/communication motes and a comprehensive sensor board, and enable them to support a priority-ensured preemptive medium access control (PP-MAC) scheme to realize a wirelessly preemptive sensing system. The first Imote2 (Imote2-1) is dedicated to providing an accurate and uninterrupted clock to the ADC and performing digital filtering on the data on the fly and on-board analysis of the data when it is not sampling; and it also provides the control channel support for the PP-MAC. The second Imote2 (Imote2-2) is in communication with the first Imote2 through the circuitry on the sensor board to exchange command and data; and it is responsible for communicating data with the network and supporting the data channel of the PP-MAC. The new design may be applied to a wirelessly preemptive sensing system for quasi-realtime earthquake monitoring of bridges and traffic overload.

7647-18, Session 3a

Embedded model updating and load characterization of wind turbines using wireless sensor networks

R. A. Swartz, A. Zimmerman, J. P. Lynch, Univ. of Michigan (United States)

The continued development of renewable energy resources is vital in the current struggle to achieve sustainability and independence for our nation's energy production. Key to that effort are reliable generators for sustainable energy sources that are economically competitive with legacy (fossil fuel) sources. In the area of wind energy, a major contributor to the cost of implementation is large uncertainty regarding the condition of wind turbines in the field due to lack of information about loading, dynamic response, and fatigue life of the structure expended. Under favorable circumstances, this uncertainty leads to overly conservative designs and maintenance schedules. Under unfavorable circumstances, it leads to inadequate maintenance schedules, damage to electrical systems, or even structural failure. Low-cost wireless sensors can provide more certainty for stakeholders by measuring the dynamic response of the structure to loading, estimating the fatigue state of the structure, and even extracting loading information from the structural response without the need of an upwind instrumentation tower. This study presents a method for using wireless sensor networks to estimate the spectral properties of the loading that a wind turbine tower is exposed to based on its measured response and some rudimentary knowledge of its structure. Exact structural parameters are estimated via model-updating in the frequency domain to produce an identification of the system. The updated structural model and the measured output spectra are then used to estimate the input spectra. Laboratory and field validation results are presented.

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7647-19, Session 3a

Wireless sensors for permanent monitoring of heritage buildings

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We report the outcomes of one year operation of a permanent monitoring system based on wireless sensors deployed on a 31 meter-tall medieval tower located in the city of Trento. What makes this monument worthy of attention is the “Cycle of the Months”, a set of frescoes decorating the room on the second floor, that remarkably represent one of most important International Gothic works in Europe. The sensors and power system were specifically selected and deployed to record expected structural response and environmental effects, and to operate unsupervised for a period of one year and more. Strain sensors include prototypes of new fiber-optics gauges in view of their long-term stability and durability. Customized hardware deals efficiently with high-volume vibration data. Dedicated software services provide: i) data collection, to efficiently reconcile the diverse data rates and reliability needs of heterogeneous sensors; ii) data dissemination, to spread configuration changes, enabling remote tasking; iii) time synchronization, with low memory demands. System operation requires techniques for processing the large amount of data acquired to develop information on the risks to the structure. The general approach used for identifying damage is based on Bayes’ principle. This methodology allows us to deal flexibly with all the uncertainties involved in the problem: measurement noise, uncertainness on the model and inaccurate prior information. In the specific case, the result of the simulated day by day risk analysis shows that the identification algorithm can highlight a hazardous condition many days in advance with respect to the actual occurrence of damage.

7647-20, Session 3b

* Design of a mobile gait monitoring system and its experimental results

J. Bae, K. Kong, M. Tomizuka, Univ. of California, Berkeley (United States)

Currently, rehabilitation treatments for gait disorders are performed by physical therapists in a clinical setting. Although an array of equipment, such as motion capture devices and multi-directional force plates, has been devised to provide the physical therapists with more objective diagnostic data, restriction of the time and space limits the effective use of such devices. To overcome this limitation, various wearable sensors for patients to directly monitor their health conditions anywhere at anytime have been studied in recent years. We have proposed a monitoring system for this purpose, which includes smart shoes. The smart shoes measure the ground contact forces by air-pressure sensors connected to air-bladders embedded in shoes. The sensing performance (e.g., linearity and accuracy) and practicality (e.g., durability) of the smart shoes have been verified in a laboratory environment. In this paper, a mobile gait monitoring system (MGMS) is introduced, which integrates the smart shoes and the monitoring algorithms in a mobile microprocessor. The mobility of the MGMS allows patients to take advantage of the gait monitoring device in their daily lives. The monitoring algorithms embedded in the MGMS observe various physical quantities useful for objective gait diagnoses, such as the gait phases, the center of ground contact forces, and the deviation of ground contact forces from a standard pattern. By the visual feedback information displayed on the LCD screen, the patients can self correct their walking patterns. The preliminary results of clinical verification are also given.

7647-21, Session 3b

Noise reduction and analysis of two time-based multi-output modal analysis techniques

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Modal analysis is a well developed field with many applications. In particular, forced response multi-output approaches are particularly well suited for online damage detection because they use the natural excitations the system undergoes during its normal operation. In this work, two of these approaches, SOD and DSPI, are analyzed and compared. SOD was originally developed as a tool for detecting damage in chaotic dynamical systems. Recently it has been used as a time-based multi-output modal analysis approach. SOD has been demonstrated to work for the free vibration case and for random excitations. DSPI was developed as a time-based multi-input multi-output approach. When the inputs are not measured, DSPI is very similar to SOD and can handle both free vibrations and random excitations. However, if the inputs are measured or known DSPI can also handle arbitrary excitations. In addition to comparing and analyzing these two methods, noise filtering algorithms are introduced for both methods to improve upon the methods when using noisy data. Numerical simulations are carried out on a variety of systems to compare the methods and to show the effectiveness of the filtering algorithms in improving frequency and mode shape extraction.

7647-22, Session 3b

An active vibration control system for spacecraft in launch vehicles

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Launch vehicle vibrations’ impact on the payload continues to be a major concern for the Launch vehicle providers as well as spacecraft manufacturers. To control these unwanted vibrations, active vibration control is studied. Active vibration control systems are closed-loop control systems and mainly based on piezoelectric transducers. Currently, the most common active vibration control systems use data acquisition boards such as dSPACE, which is connected to a PC. The large size and weight of such control systems would not make it effective for a spacecraft launch vehicle. We propose to employ an embedded computer with an integrated sensing and actuation control board for active vibration control in spacecraft launch vehicles.

Finite element analysis was used to find the modal frequencies and the modal shapes of the cantilever beam. The optimal placement locations for the piezoelectric sensor and actuator were found by comparing where the mode shape and its derivative had the same trend. It was also necessary to view where the areas of zero strain were located; this was found by taking the second derivative of the mode shapes. If an actuator is place where an area of zero strain is located the force produced by the actuator will be decreased. To meet the two conditions, the actuator was placed near the fixed end of the cantilever beam. A cantilever beam with a shaker was set up for the experimentation study. The cantilever beam had a piezoelectric sensor and actuator bonded on the beam to control the vibrations.

7647-23, Session 3b

* Fast estimation of bifurcation conditions using noisy response data

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Dynamic bifurcations often correspond to dramatic changes in system response that can be utilized for sensing purposes. This is conveniently

applicable in micro- and nano-scale resonators that are subjected to harmonic excitation. Of interest here is the case of parametric resonance, in which the system response is essentially at the noise floor, except in a resonance zone that occurs at nearly twice the device natural frequency. These subharmonic resonance bifurcations are currently being developed for use in MEMS mass sensors and rate gyros. Depending on the level of noise present and the sweep rate, the response jump can be premature or delayed relative to the actual bifurcation point. A fundamental issue that must be addressed is the determination of the bifurcation parameter condition from a collection of response jump parameter values, obtained from parameter sweeps. The purpose of the proposed work is to provide a quantitative estimate, and confidence information, for the bifurcation parameter value from this data. We use tools from stochastic nonlinear dynamical systems to examine this problem in terms of noise-activated escape from a diminishing potential, and we attack the general problem by solving a Fokker-Plank equation for the escape problem with a parameter sweeping through the bifurcation. It is shown that nonadiabatic sweeping can provide more accurate and faster measurements than adiabatic (quasi-static) sweeping, and an optimal sweep strategy is derived. The theory is applied to a model and experimental data for a parametrically forced microbeam.

7647-24, Session 3b

* A new approach to tackle noise issue in miniature directional microphones: bio-inspired mechanical coupling

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One of the key factors limiting the application of miniature directional microphones is the noise. In this article, a theoretical investigation is conducted to compare the three approaches to construct a directional microphone, including a conventional microphone pair, a pressure gradient (first-order) microphone combined with a pressure sensor, and a mechanically coupled directional microphone inspired by the superacute ear of the parasitoid fly Ormia ochracea. Given the same detection method to measure the diaphragm deflection and same noise floor, it is found out that the mechanically coupled design can achieve much higher resolution than the other two methods. Numerical simulation also demonstrates that this bio-inspired design is able to accommodate much lower signal-to-noise ratio in the incident acoustic signals. This work provides an indirect evidence explaining how the fly ear achieves directional sensitivity comparable to the human ears while it has sub-millimeter interaural separation and much fewer number of neuron cells. It also serves as a theoretical support for applying the fly ear mechanism to the development of miniature directional microphones.

7647-25, Session 3b

Adaptive damping of piezoelastic structures via digital implementation of inductor-resistor shunts

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This contribution is concerned with adaptive damping of plate-like structures equipped with a piezoelectric patch. It is well known in the literature that damping of mechanical modes can be accomplished by connecting an electrical impedance, e.g. an inductor-resistor shunt, at the terminals of the piezoelectric patch. The electrical circuit, however, needs to be tuned quite exactly to achieve good damping performance around the desired mechanical eigenfrequency. Also, mechanical structures are exposed to varying environmental conditions which lead to a non-negligible shift in mechanical eigenfrequencies and de-tuning of the resonant circuit. The authors, hence, propose the algorithmic implementation of the electrical behavior of the inductor-resistor shunt on a microcontroller. The digital approach also enables the microcontroller to perform system identification and monitor the mechanical eigenfrequencies of the structure. This information is subsequently used for updating the parameters of the algorithm mimicking the inductor-resistor shunt. The performance of the electronic circuit is evaluated on a homogeneous rectangular glass plate with a C-F-C-F boundary condition, i.e. two opposite edges either clamped or free. The plate is equipped with a piezoelectric patch which is placed in the center of the plate to influence damping of the 1-n plate eigenmodes with n being an odd number. Excitation of the plate is achieved by an acoustic source and plate vibrations are recorded with a Laser scanning Doppler vibrometer. Simulation and experimental data along with analyses on the adaptation of the software parameters with respect to variations in the mechanical eigenfrequencies are presented.

7647-27, Session 4a

Integrated PZT/FBG guided wave generation and sensing system using a single laser source

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Guided waves based structural health monitoring (SHM) techniques have been of great concern to many researchers. Among various kinds of SHM devices, lead zirconate titanates (PZTs) and fiber Bragg gratings (FBGs) have been widely used for guided wave generation and sensing. To utilize their merits, integration of PZT-based actuation and FBG-based sensing has been developed by many researchers. This integrated PZT/FBG system is widely known as a technique that enables the decoupling of actuation and sensing channels to prevent electromagnetic interference (EMI). For wide application of this technique, this study proposes an integrated PZT/FBG system using a single laser source. Since this system is based on optic devices such as a tunable laser and fiber optics, it is possible to avoid technical problems regarding the electrical power cablings such as complicated cabling setups, and power attenuations. Also, simultaneous measurement of multiple parameters is possible by using FBG sensors which are good for multiplexing. The experimental procedure for the proposed system is as follows. First, a tunable laser is used as the common power source for guided wave generation and sensing. Then, one laser beam is modulated and amplified to actuate the PZT. The other laser beam is used with the FBG sensor to measure high-speed strain changes induced by guided waves. The feasibility of the proposed technique has been experimentally demonstrated using an aluminum plate. The results show that the proposed system could properly generate and sense the guided waves compared to the conventional methods.

7647-28, Session 4a

Laser induced highly nonlinear solitary waves for structural NDE

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This paper describes the generation and detection of highly nonlinear solitary waves (HNSWs) in a chain of steel beads excited by using laser pulses. Ablative generation of mechanical stress was induced on the bead at one end of the chain in order to enhance the amplitude of the stress waves generated. Compared to the use of a mechanical striker, the laser-based generation of stress waves is fully non-contact and allows for the broadest energy spectrum. In this study the amplitude, duration, and velocity of the solitary waves propagating along the chain of beads as a function of the laser pulse energy is investigated. Moreover the effect of chain pre-compression induced by means of an electromagnet is presented and discussed. Finally the application of HNSW as a pulse generator for the NDE of bulk structures is shown.

Conf. 7647: Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems

7647-192, Session 4a

Magnetic Nanoparticle (MNP) enhanced biosensing by Surface Plasmon Resonance (SPR) for portable devices

J. L. Wang, Z. Z. Zhu, A. Munir, S. H. Zhou, Worcester Polytechnic Institute (United States)

The use of magnetic nanparticles in microfluidic systems is emerging and is receiving growing attention due to the synergistic advantages of microfluidics and magnetic nanoparticles. Biomagnetic separation techniques based on magnetic nanoparticles are becoming increasingly important with a wide range of possible applications. However, the separation products are difficult to be detected by general method due to the small size of MNPs. Here, we demonstrate magnetic nanoparticles can greatly enhance the signal of surface plasmon resonance spectroscopy (SPR). Features of MNPs-aptamer conjugates as a powerful amplification reagent for ultrasensitive immunoassay are explored for the first time. Our results confirm that MNPs is a powerful sandwich element and an excellent amplification reagent for SPR based sandwich immunoassay and SPR has a great potential for the detection of magnetic nanoparticles-based separation products.

7647-30, Session 4b

Optical fiber sensors for high temperature harsh environment applications

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Sensors for harsh and extreme environments demand non-reduced accuracy and supreme robustness. Optical fiber sensors (OFS), with their all glass nature, small size, corrosion resistance, electromagnetic immunity, and high resolution, are considered a promising candidate for various sensing applications in high temperature hash environments. This paper summarizes our recent research progresses in developing various harsh environment sensors for various engineering applications.

High-temperature tolerant long period fiber gratings (LPFG) and core-cladding mode interferometers (CCMI) were developed to monitor and assess the structural condition of critical buildings in an earthquake-induced fire environment. Both sensors were fabricated by controlled CO2 laser irradiations for operation in high temperature environments. Their axial strain measurement properties were studied at high temperatures (up to 700ºC). Investigations have also been conducted to use these sensors for simultaneous temperature and strain measurements.

Fiber inline Fabry-Perot interferometers (FIFPI) were fabricated by femtosecond (fs) laser micromachining for temperature, strain and dynamic pressure measurements in high temperature harsh environments. The sensor had a high-quality interference fringe and survived temperatures upto 1100 C. A diaphragm based FIFPI sensor was designed and fabricated for in situ monitoring of the dynamic pressures inside an auto-ignited combustion engine. The sensor probe was packaged and tested inside an engine operating at a temperature around 800ºC. The sensitivity and frequency response were evaluated experimentally. Structural parameters of the FIFPI sensor such as the diagram diameter and thickness were investigated to optimize the sensor performance.

7647-31, Session 4b

* Micro-machinable polymer-derived ceramics sensors for high-temperature applications

J. Liu, C. Xu, L. An, Univ. of Central Florida (United States)

Micro-sensors are highly needed for on-line temperature/pressure monitoring in turbine engines to improve their efficiency and reduce pollution. The biggest challenge for developing this type of sensors is that the sensors have to sustain at extreme environments in turbine engines, such as high-temperatures (> 800oC) and oxidation/corrosion surroundings. In this paper, we describe a certain class of sensors made of polymer-derived ceramics (PDCs) for such applications. PDCs have the following advantages over conventional ceramics, making them particularly suitable for these applications: (i) micromachining capability, (ii) tunable electric properties, and (iii) high-temperature capability. Here, we will discuss the materials and their properties in terms of their applications for high-temperature micro-sensors. In addition, we will also discuss two types of micro-sensors: (i) heat-flux sensor and (ii) pressure sensor, which are made from polymer-derived ceramics.

7647-32, Session 4b

* Non-contact torque measurement using rolled single crystal-like Galfenol patches

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Galfenol is an iron-gallium alloy that exhibits magnetostrictive behavior up to approximately 400ppm. It has been shown that Galfenol exhibits a linear response in strain that follows commercially available strain gauges when a magnetic bias field is placed near the Galfenol patch in a bending test. In this study we extend these results to use of a Galfenol patch for measuring torque. The benefits of Galfenol-based torque sensors over existing strain sensors for measuring torque are (1) the potential for use of stray magnetic fields for non-contact torque measurement; (2) ease of integration and/or retrofit of the proposed torque measuring capability into existing hardware; and (3) an inexpensive yet mechanically robust alternative to torque sensors that require slip rings or wireless signal transmission. This Research will show that when placed on a circular shaft at ± 45o relative to the shaft axis Galfenol will exhibit a linear response to shear strain on the shaft. By showing that measurement of shear strain is possible it is evident that the torque on the shaft can also be determined. A hall sensor will be rigidly attached to a non-rotating component of the measurement frame supporting the shaft, and used to determine the change in the magnetic field above the patch. While the shaft is rotating the response from the hall sensor is monitored to determine the torque load on the shaft.

7647-33, Session 5a

* Smart pavement sensor based on thermoelectricity power

X. Yu, Case Western Reserve Univ. (United States)

The aging infrastructure requires a proactive strategy to ensure their functionality and performance. Innovative sensors are needed to develop infrastructures that are intelligent and adaptive. A power supply strategy is among the crucial components to reduce the instrument cost and to ensure the long term function of these embedded sensors. This paper introduces the results of a preliminary study on using thermo-electricity generation to power sensors. This presents an innovative strategy for long term monitoring of pavement performance.

7647-34, Session 5a

Experimental investigation of a smart FRP-concrete composite bridge superstructure

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Fiber reinforced polymer (FRP)-concrete composite bridge

superstructure is a type of newly developed structure. It behaves brittle failure at its peak strength, and so the health monitoring of the FRP part is essential for the life-cycle safety of the structure. Optical fiber Bragg grating (FBG) sensor is broadly accepted as a structural health monitoring device for FRP materials by either embedding into or bonding onto the structures. Herein, a new kind of smart FRP-concrete composite bridge superstructure, which consists of FRP box sections combined with a thin layer of concrete in the compression zone, was developed by using eight embedded FBG sensors in the top and bottom flanges of FRP box sections at mid-span section along longitudinal direction, respectively. Fabrication process of the proposed smart FRP-concrete composite bridge superstructure was introduced. The flexural behavior of the smart composite bridge superstructure was experimentally studied in 4-points loading. The longitudinal strains of the FRP box sections were recorded using the embedded FBG sensors as well as the surface-bonded electric resistance strain gauges. Test results indicate that the FBG sensors can faithfully record the longitudinal strain of the FRP box sections in tension at bottom flange or in compression at top flange, as compared with the surface-bonded strain gauges. The proposed smart FRP-concrete composite bridge superstructure can reveal its true internal strain over the entire load range, and will have wide applications for long-term monitoring in civil engineering.

7647-35, Session 5a

Foot angle determination using conductive polymer sensors

L. M. Castano, Univ. of Maryland, College Park (United States)

A study was carried to assess the possible monitoring of joint angles, foot posture and foot motion through the use of conductive polymer sensors. The sensors are composed of a carbon polymer coating on an elastic fabric and they present a strain gauge behavior. A hinge was used as an angle generator and a sensor strip was clamped longitudinally across the hinge. An electrogoniometer was used to monitor the angle spanned by the two wings of the hinge. Series of simultaneous measurements of angle and resistance were conducted at different speeds. Results indicate that a range of resistance differentials can be assigned to an angle span regardless of speed. The amplitude of the Fourier transform of the resistance measurements also had a defined range for each angle span i.e. 10 to 20, 10 to 40, etc... degrees. This would imply that the angle span could be determined at any flexing speed based on resistance measurements, enabling real time monitoring. Four carbon sensors were then applied on socks and were placed on different locations of maximum strain on the foot. Different sets of sensor locations were assessed for a better sensor response. A correlation was found among the waveforms of the resistance signals outputted by each of the sensors for different types of foot motion. This was also characterized by wavelet analysis of each set of resistance measurements for short periods of time. The smart socks intend to aid in the gait detection and rehabilitation of patients with walking disabilities.

7647-36, Session 5a

Smart composite based on field emission and tunneling effects and its piezoresistive characteristic model

B. Han, J. Ou, Harbin Institute of Technology (China)

A highly sensitive piezoresistive inorganic composite fabricated from cement-matrix and nickel powders is reported. The electrical resistivity of such composite decreases 69.00% under uniaxial compression (the electrical resistivity decreases 62.61% within the elastic regime). The sensitivities of this composite to compressive stress and strain are higher than 0.05/MPa and 895.45 respectively. These extremely high piezoresistive properties are attributed to the unique needle-like surface morphology of nickel powers. Comparing to the normal smooth spherical nickel particles, the needle-like features of spiky spherical nickel particles can induce field emission and tunneling effects, which leads to highly sensitive responses to compressive stress/strain.

A constitutive model relating the change in the electrical resistivity to the applied compressive stress of cement-based composites containing nickel powders with needle-like surfaces is also developed. This model incorporates the field emission effect and the inter-particle separation change of nickel powders in composites within elastic regime under uniaxial compression. The model is used to predict the piezoresistive characteristic behavior of cement-based composites containing nickel powders with different particle sizes. The predicted results are compared with the experimental data obtained on three kinds of composites, and good agreements are obtained.

7647-37, Session 5b

Multifunctional sensor network for structural state sensing

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In order to take full advantages of composites and enable future composite structures to operate at their physical limits rather than limits predetermined from computational design assumptions and safety factors, there is a need to develop an embeddable sensing system to allow a structure to “feel” and “think” its structural state. In the paper, the concept of multi-modal sensing capabilities using a network of multifunctional sensors integrated with a structure in developed. Utilizing this revolutionary concept, future structures can be designed and manufactured to provide multiple modes of information that when synthesized together can provide capabilities for intelligent sensing, environmental adaptation and multi-functionality. To demonstrate the feasibility of multi-modal sensing capabilities with built-in sensor network, one single type of piezoelectric sensor was selected to perform the measurements of dynamic strain, temperature, damage detection and impact monitoring. The uniqueness of the sensing system includes (1) Ultra-thin film, flexible, multifunctional sensor networks for integration with any type of unitized composite structural component, (2) Scalable sensor network for monitoring of a large composite structure, (3) Reduced number of connecting wires for sensors, (4) Hybrid diagnostics with multiple sensing capabilities, (5) Sensor network self-diagnostics and self-repair for damaged sensor system.

7647-38, Session 5b

SMART composite high pressure vessels with integrated optical fiber sensors

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In this paper application of integrated Optical Fiber Sensors for strain state monitoring of composite high pressure vessels is presented. The composite tanks find broad application in many areas such as: automotive industry, aeronautics, rescue services, etc. In automotive application they are mainly used for gaseous fuels storage (like CNG or compressed Hydrogen). In comparison to standard steel vessels, composite ones have many advantages (ie. high mechanical strength, meaningful weight reduction, etc).

In the present work a novel technique of vessel manufacturing, according to this construction, was applied. It is called braiding technique, and can be used as an alternative for winding method. During braiding process, between GFRC layers, two types of optical fiber sensors were installed: point sensors in form of Fiber Bragg Gratings as well as interferometrical sensors with long measuring arms (SOFO®). An integrated optical fiber sensors create a nervous system of the pressure vessel and are used for its structural health monitoring (SHM). OFS register deformation areas and detect construction damages in its early stage (ensure a high safety level for users). Applied sensor system proved also a possibility of strain state monitoring even during vessel manufacturing process.

OFS sensors can be inbuilt in the structure of composite material without changing its mechanical properties. Moreover, OFS sensors are spark less and resistant against electromagnetic disturbance. They have large range of measurements and well collaboration with other electric systems of cars, enabling tank's on-line or periodical monitoring.

7647-40, Session 5b

Magnetostrictive unimorph transducer network model

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A new rotational magnetomechanical transducer network model for a magnetostrictive unimorph is presented. Such a magnetostrictive unimorph structure reacts with bending to an appropriate directed magnetic field and can be used as actuator. A forced bending of the unimorph changes the magnetic properties of the magnetostrictive layer which is the basis for sensor and energy harvesting applications. A transducer setup defines often an operating point about which the mechanical, magnetic and electrical quantities show only small variations which can be linearized. Taking the component geometries into consideration a lumped parameter circuit representation of the magnetomechanical and electromechanical system can be derived. It is a useful tool for understanding and explaining the behavior of systems involving different physical domains. It is shown that the magnetomechanical transduction coefficient in actuation direction, which is obtained via classical laminated plate theory, holds also for the sensing relation. The magnetomechanical model can be combined with electromagnetic coil models to include the electrical domain. The electromagnetic and the magnetomechanical transducer are connected by a magnetic voltage divider which takes the spatial magnetic field distribution into account. The presented models can be used for a fast analysis of existing systems and also for the optimization of new designs. The resulting circuit description can be simplified, e.g. to a single impedance, by transforming network elements into other domains. Both the actuation and sensing behavior of a laminated magnetostrictive Al-Galfenol composite are experimentally investigated and the transduction coefficient is determined.5EYX

7647-193, Session 5b

On electrostatically actuated microsensors

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This paper deals with electrostatically actuated mass sensing cantilever resonators. Nonlinear parametric resonances are present in the system. The principle of mass detection resonator sensors is the change in frequency due to mass deposition. Resonator sensitivity used in this work is defined as the fraction of change in frequency per unit mass. The hypotheses of this work are: 1) the sensor is a coated with molecular recognition chemistry Euler-Bernoulli cantilever beam, 2) the thickness of the deposited film is constant, 3) the thickness of the deposited film is very small compared to any of the beam dimensions, 4) the deposition occurs on all sensor lateral surfaces, and 5) the film mass it is small but not negligible compared to the total mass of the sensor-film system, and 6) the sensor is electrostatically actuated (nonlinear parametric force).

Analytical results are obtained by applying the method of multiple scales directly to the differential equation of motion. The original boundary value problem results into two simpler boundary value problems to be solved. The first problem consists of a homogeneous partial differential equation along with its boundary conditions. The second problem consists of a nonhomogeneous partial differential equation and boundary conditions that provides the influence of the deposited mass on the nonlinear parametric resonance of the sensor. A survey of the literature shows the importance and the large number of applications for sensors. Several applications deal with detecting the presence of proteins, mercury vapor, etc., using either one or arrays of cantilever resonator sensors. Recent papers presented an interest in developing biosensors arrays that are based on micro-fabricated resonators coated with molecular recognition chemistry. The ultimate goal was to integrate hundreds of miniature resonators within a single chip for detection of biological species. Microresonator sensors were used to detect virus particles, bacteria, gas, and vapor. Mercury vapor in the air was detected using microsensors coated with a thin gold film.

7647-41, Session 6a

Distributed wireless sensor network for structural health monitoring using embedded piezoelectric transducers

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Piezoceramic based transducers are widely researched and used for structural health monitoring (SHM) systems due to the piezoceramic material's inherent advantages of dual sensing and actuation ability. Wireless sensor network (WSN) has the benefit of easy and flexible installation, low system cost and increased robustness over wired system. However, piezoceramic based wireless SHM systems still faces drawback as they require relatively high computational capabilities for calculating damage information, on the other hand battery powered WSN sensor nodes have strict power consumption limitation and hence limit computational power. Although commonly used centralized processing networks can provide sufficient computational capability, it requires wireless sensors to transmit all data back to the network coordinator for analysis, which is neither energy efficient nor robust. In this paper, we aimed to solve these problems with a distributed wireless sensor network for piezo-base SHM systems. Instead of sweep sine excitation that was used in early research, several sine frequencies were used in sequence to excite the concrete structure. The wireless sensors record the sine excitations and compute the time domain energy for each sine frequency locally to detect the energy change. By comparing the data of the damaged concrete frame with the healthy data, we are able to find out the damage information. A relative powerful wireless microcontroller was used to carry out the distributed data processing in real-time. The distributed wireless network dramatically reduced the data transmission between wireless sensor and the wireless coordinator, which in turn reduced the power consumption of the overall system.

7647-42, Session 6a

The combined use of low-cost smart sensors and high accuracy sensors to apprehend structural dynamic behavior

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Wireless smart sensors equipped with computational and wireless communication capabilities are expected to provide rich information for structural health monitoring (SHM); inexpensive nature of sensors nodes and wireless communication allows dense sensor instrumentation over structures. While dense measurement is advantageous with regard to spatially characterizing structural dynamic behaviors, limited sensing accuracy of inexpensive wireless sensor nodes possibly bounds applications. For example, small ambient vibration may not be captured by smart sensor nodes. Weakly excited modes may not be well captured. Though the use of better accuracy sensors might be considered obvious solution, the increase in sensor node cost abates one of merits of wireless smart sensor usage, i.e., inexpensiveness.

This paper proposes a combined use of low-cost smart sensors and high accuracy sensors for dynamic measurement of a bridge to alleviate the influence of this limitation. In addition to inexpensive smart

sensor nodes densely instrumented on structures, a smaller number of high accuracy sensors are installed. Signals from these two sets of sensors are analyzed together to take advantage of the dense sensor arrangement and high accuracy sensors. Numerical simulation shows the effectiveness of this approach. The use of two sets of data is then applied to vibration measurement of a full-scale cable-stayed bridge. This field application demonstrates the potential capability of smart sensors to capture dynamic behavior of structures in detail.

7647-43, Session 6a

SHMTools: a new embeddable software for SHM applications

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This paper introduces a new software tool for various structural health monitoring (SHM) applications. The SHM paradigm has been cast in the framework of statistical pattern recognition, promoting data driven damage detection approaches. To reflect this paradigm in SHM and to allow user-friendly analyses of data, new software, referred to as “SHMtools” is developed. This software is a set of standardized modules of MATLAB code covering the four categories of statistical pattern recognition as applied to SHM: data acquisition, data normalization, feature extraction, and feature analysis for damage identification. Input and output parameters are standardized so that custom SHM processes are easily assembled by merely specifying a set of functions from each of these modules. The detection algorithms are an embeddable subset of an open source package designed to facilitate the assembly of custom SHM processes. The embeddable subset consists of functions which can be cross-compiled into generic “C” programs. Embedding the algorithms onto hardware then consists of compiling the embeddable subset into executables using a “C” cross-compiler optimized for the targeted hardware. The software is also designed to accommodate multiple sensing modalities, including piezoelectric active-sensing, which has been widely used in SHM practice.

One of the hardware designed to embed the SHMtools is a custom wireless embedded system, referred to as SHiMmer. SHiMmer is a stand-alone platform capable to perform active-sensing SHM measurement. SHiMmer system comprises three independent components: a Digital board for data analysis and communications running a custom Linux-based OS, an Analog board that manages 16 channels connected to piezoelectric sensors for SHM measurements, and a power manager module.

The details of this embeddable software and hardware will be discussed, along with several example processes that can be used for guidelines for future use of the proposed technology.

7647-44, Session 6a

Decentralized data aggregation in wireless smart sensor network

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Wireless Smart Sensor Networks (WSSN) facilitates a new paradigm to structural identification and monitoring for civil infrastructure. Conventionally, wired sensors and central data acquisition systems have been used to characterize the state of the structure, which is quite challenging due to difficulties in cabling, high equipment cost, and long setup time. The WSSN offers a unique opportunity to overcome such difficulties. Recent advances in sensor technology have realized low-cost, smart sensors with on-board computation and wireless communication capabilities, making deployment of a dense array of sensors on large civil structures both feasible and economical. However, as opposed to wired sensor networks in which centralized data acquisition and processing are a common practice, the WSSN requires decentralized approaches due to the limitation associated with wireless communication; to date implementation of such approaches in the WSSN are limited. This study presents a decentralized data aggregation scheme implemented in the WSSN employing Crossbow Imote2 sensors. Rather than collecting sensor data centrally, the onboard processing unit is utilized to obtain two commonly used data in the structural identification: (1) correlation function of the Natural Excitation Technique and (2) pseudo impulse response function of the Random Decrement Method. The efficacy of the decentralized data aggregation scheme in the WSSN is experimentally verified.

7647-45, Session 6a

* Validation of a wireless sensor network using local damage detection algorithm for beam-column connections

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There has been a rapid advancement in wireless sensor network (WSN) technology in the past decade and its application in structural monitoring has been the focus of several research projects. The evaluation of the newly developed hardware platform and software system is an important aspect of such research efforts. Although much of this evaluation is done in the lab and using generic signal processing techniques, it is important to validate the system for its intended application as well. In this paper the performance of a newly developed accelerometer sensor board is evaluated by using the data from a beam-column connection specimen with a local damage detection algorithm. The sensor board is a part of a wireless node that consists of the imote2 control/communication unit and an advanced antenna for improved connectivity. A scaled specimen of a steel beam-column connection is constructed in ATLSS center at Lehigh University and densely instrumented by synchronized networked systems of both traditional piezoelectric and wireless sensors. The column ends of the test specimen have fixed connections, and the beam cantilevers from the centerline of the column. The specimen is subjected to harmonic and white noise excitations in several test runs and its accelerometer response is collected by both systems. The collected data is then used to estimate two sets of system influence coefficients with the wired one as the reference baseline. The performance of the WSN is evaluated by comparing the quality of the influence coefficients and the rate of convergence of the estimated parameters.

7647-46, Session 6b

Compact sensitive piezoelectric mass balance for measurement of unconsolidated materials in space

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In many in-situ instruments information about the mass of the sample could aid in the interpretation of the data and portioning instruments may require accurate sizing of the mass before dispensing the sample. In addition, on sample return missions a method to directly assess the collected sample quantity is required to determine if the sampler can return or needs to acquire another sample. In an effort to meet these requirements we have developed piezoelectric balances using flextensional actuators which are capable of monitoring the addition of mass using two methods. A piezoelectric balance can be used to measure mass directly by monitoring the voltage developed across the piezoelectric which is linear with force or it can be used in resonance to produce a frequency change proportional to the mass change. If a small mass is added to the balance the resonance frequency shifts down proportionally to the mass. By monitoring the frequency shift the mass can be determined. This approach allows for two independent measurements of the mass. In microgravity environments spacecraft

thrusters could be used to provide acceleration in order to produce the required force in the first technique or to bring the mass into contact with the balance in the second approach. In addition, the measuring actuators could be driven at higher voltages to fluidize the powder to aid sample movement. In this paper, we describe our design considerations and present the results obtained using prototype balances that we developed.

7647-47, Session 6b

* Mechanisms of sliding friction studied with an array of industrial conical piezoelectric sensors

G. McLaskey, S. D. Glaser, Univ. of California, Berkeley (United States)

In this study, we use a new design of high-fidelity nanoseismic sensors to detect the stress waves produced at the initiation of sliding during stick-slip friction. The reported experiments are designed to provide insights that may be applicable to both fault scales and micro contact junctions. The sensors used are packaged in a hardened steel case to facilitate their use in the field. The transducer's small size (15 mm threaded body, 30 mm long) permits a dense population of sensors to be installed on laboratory-sized samples, or surrounding localized centers of damage on structural applications. The piezoelectric sensors can detect radiated waves just a few pm in amplitude in the frequency range of 10 kHz to over 2 MHz, and therefore have the ability to identify load drops down to about 10 mN. The closely spaced sensor array facilitates the localization of individual load releases from tiny asperities on a cm-scale frictional interface. At the same time, the broadband response of the conical piezoelectric sensors makes possible the study of source dynamics using theory developed for the study of Earthquake source mechanisms via radiated seismic waves.

7647-48, Session 6b

Direct measurement sensor of the boundary shear stress in fluid flow

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The flow fields and boundary erosion that are associated with scour at bridge piers are very complex. In particular, scour development is complicated by the important effects of large scale turbulence structures (macro-turbulence) that markedly characterize pier flow fields. The role that such turbulence structures play in scour has only been partially appreciated. It is a role that needs to be very well-understood when investigating scour at bridge piers. Turbulence structures, together with local flow convergence / contractions around the fronts and flanks of piers, or between piles of complex pier configurations, are erosive flow mechanisms of primary importance. The interactions of macro-turbulence structures with converging flows are of key significance in illuminating how pier geometry affects sediment entrainment and thereby scour morphology and maximum scour depth. Direct measurement of the boundary shear stress and boundary pressure fluctuations in experimental scour research has always been a challenge and high spatial resolution and fidelity have been almost impossible. Most researchers have applied an indirect process to determine shear stress using precise measured velocity profiles. Laser Doppler Anemometry and Particle Image Velocimetry are common techniques used to accurately measure velocity profiles. These methods are based on theoretical assumptions to estimate boundary shear stress. In addition, available turbulence models cannot very well account for the effect of bed roughness which is fundamentally important for any CFD simulation. The authors have taken on the challenge to advance the level at which direct measurements of the shear stress in water flow can be performed. This paper examines the development of a higher accuracy and small spatial resolution sensor including the challenges. Preliminary sensor designs and test results will be presented in this paper.

7647-49, Session 6b

Multipoint fibre optic voltage sensor

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In this paper we propose a new approach to fibre optic voltage sensors via a voltage-controlled Liquid Crystal (LC) cell, which would allow direct measurement of up to 400 kV/m electric fields at multiple points along a power line. The voltage applied to the cell is harvested by probe (antenna) from the electric filed created by high voltage transmission lines.

7647-50, Session 6b

Study on in-line fiber-optic sensor using near-infrared spectroscopy

H. Wang, Y. Peng, South China Univ. of Technology (China)

A methodology for monitoring extrusion process using in-line fiber-optic near-infrared spectroscopy is present in this paper. Fiber-optic sensor and sensing system are also designed. Predictive calibration models of NIR spectra are developed for monitoring of polymer composition and concentration by using multiple linear regression techniques and artificial neural networks. It is important to study nucleation of microcellular plastics.

7647-51, Session 7a

Structural health monitoring for ship structures using time series models

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Currently the Office of Naval Research is supporting the development of structural health monitoring (SHM) technology for U.S. Navy ship structures. This application is particularly challenging because of the physical size of these structures, the widely varying and often extreme operational and environmental conditions associated with these ships' missions, lack of data from known damage conditions, limited sensing that was not designed specifically for SHM, and the management of the vast amounts of data that can be collected during a mission even with this limited sensing. This presentation will discuss ship structure SHM challenges in the context of applying various SHM approaches to sea trials data measured on an aluminum multi-hull high-speed ship, the HSV-2 Swift. In particular, linear and nonlinear time series models are shown to be a very effective tool for modeling the sensors' response during sea trials, establishing correlation between widely distributed sensors and identifying anomalous conditions.

7647-52, Session 7a

Corrosion monitoring of reinforcing steel in concrete by electrochemical sensors

G. Qiao, Harbin Institute of Technology (China)

Health degradation by corrosion of steel in civil engineering, especially in rough environment, is a persistent problem. A novel all solid state-current confined corrosion sensor has been developed to provide the platform for corrosion monitoring of the steel bar in concrete beam by electrochemical method. Finite element method has been

used to optimize the geometric configuration of the corrosion sensor. The numerical results show that the corrosion sensor can effectively confine the current in the fixed area which is 45mm×π×Dsteel bar. Then the sensors have been used in the concrete beams to monitor the corrosion of the steel bar. The monitoring results of the sensors show that the magnitudes of the corrosion rate of the steel bar are from 10-7μA/cm2 to 10-5μA/cm2 before and after corrosion. It can be concluded that the optimized corrosion sensor can confine the excited current effectively and monitor the corrosion condition of the steel bar accurately. The multi-point distribution and in-situ corrosion monitoring can be realized by using the corrosion sensor in the field.

7647-53, Session 7a

Prestress-force monitoring of PSC girder bridges using wireless impedance sensor nodes

J. Park, J. Kim, Pukyong National Univ. (Korea, Republic of)

To date, many prestressed concrete (PSC) girder bridges have been constructed since the compressive prestress makes more economical use of the concrete. Therefore prestress force in tendon is an important parameter that should be secured for its safety against external loadings and environmental conditions. Recently, electro-mechanical impedance-based health monitoring has shown the promising success to detect minor changes in structural integrity. While the impedance-based health monitoring is efficient, the costs associated with installation and maintenance of the impedance-based monitoring system can be very high. The high costs of the system can be greatly reduced through the adoption of wireless sensor node. However, the wireless impedance sensor node has measurable range with narrow frequency band which is relatively smaller than commercial impedance analyzers.

In this study, a technique using wireless impedance sensor nodes is proposed to monitor prestress-force in PSC girder bridges. In order to achieve the goal, the following approaches are implemented. Firstly, a wireless impedance sensor node is designed for automated and cost-efficient prestress-loss monitoring. Secondly, a prestress-loss monitoring technique using an interface plate is proposed to overcome limitations of the wireless impedance sensor node such as measureable frequency ranges with narrow band. Thirdly, an impedance-based algorithm is embedded in the wireless impedance sensor node for autonomous structural health monitoring. Finally, the feasibility and applicability of the proposed technique are evaluated in a lab-scaled PSC girder model for which several prestress-loss scenarios are experimentally monitored by the wireless impedance sensor node.

7647-54, Session 7a

Application of self-sensing BFRP bars into concrete structures

Y. Tang, Southeast Univ. (China); Z. Wu, Ibaraki Univ. (Japan); C. Yang, G. Wu, L. Zhao, S. Song, Southeast Univ. (China)

In this paper, a new type of self-sensing basalt fiber reinforced polymer (BFRP) bars was buried into some concrete structures to investigate the sensing performance with using the Brillouin scattering-based distributed optical fiber sensing technique, while the mechanical performance was paid attention as well. First, one of the smart bars was applied to strengthen a 2m long concrete beam with a 4-points static loading model in the laboratory. During this experiment, the bar measured the inner strain changes well, especially caught the randomly distributed cracks. With the distributed strain information along the bar, the distributed deformation of the beam and moments of each cross area can be calculated, therefore, the structure health can be evaluated. Then, the two smart bars with a length of about 70m were embodied into a concrete airfield pavement reinforced all by long BFRP bars. In this field test, all the optical fiber sensors in the smart bars survived the whole concrete casting process and worked healthily. From the measured data, the concrete shrinkage along all the pavement length could be found obviously. The experimental results in this paper also confirmed that the bar would give good strengthening in the beam, especially after the steel bar's yielding, and control the development of cracks due to the concrete shrinkage well. All the results confirm that this new self-sensing BFRP bar will show not only good sensing performance but also mechanical performance in the concrete structures.

7647-55, Session 7a

Coordinated sensing and autonomous repair of pressure vessels and structures

D. R. Huston, D. H. Hurley, K. Gollins, A. Gervais, The Univ. of Vermont (United States)

This paper discusses coordinated sensing and autonomous self-repair of structural systems. The underlying principle of autonomous repair techniques is to embed redundant capability into the structural system and to then use the redundant capability to repair and carry the load of the damaged components. Self-healing materials in the form of self-sealing fluid containment vessels have been used in man-made structures for millennia. Engineered self-healing materials have been in use in applications such as tires and airplane fuel tanks for over a century. The bulk of these techniques have the damage initiate the repair response in the material directly without any intermediate sensing and control. This research expands and demonstrates the enhancement of autonomous repair techniques through the coordinated damage sensing and directed repair activities with test bed pressure vessels and structural panels that have been damaged by puncture and drilling of holes. Acoustic emission, embedded optical and capacitance sensors detect the damage. Electrorheological, shear thickening and thermoplastic repair techniques are initiated upon repair detection and localization of damage. Autonomous leak repair in pneumatic pressure vessels and panels with perforations up to 3 mm upon detection and localization of the damage are demonstrated.

7647-56, Session 7a

Structural identification of progressive damage states in concrete columns subject to seismic excitations

Z. Wu, A. P. Adewuyi, Ibaraki Univ. (Japan); S. Xue, Kinki Univ. (Japan)

The traditional post-seismic visual inspection of structures, though provides knowledge about the vulnerability of structural systems and mechanisms of failure, they are often unreliable for effective maintenance-based monitoring against major earthquakes. In recent years, significant efforts have been devoted to developing non-destructive techniques for damage identification in structures. Prompt monitoring and accurate measurement structural characteristics are very essential for reliable condition evaluation and early detection, localization and estimation of severity of damage in structures. This paper investigates the application and evaluation of structural health monitoring (SHM) techniques for concrete columns subject to ground motions. The progressive damage states of the structure is studied based on the structural dynamic response of the eccentrically loaded reinforced concrete columns of square cross-section of side 150 mm and overall height 1200 mm mounted on a shaking table and subjected to different seismic excitations of increasing intensities. The dynamic responses to different excitations were measured using long-gage fiber Bragg grating (FBG) sensors, dynamic strain gauges and piezoelectric accelerometers installed on the two adjacent surfaces of the columns. An array of six long-gage FBG sensors of gauge lengths 200 mm were installed on each face in a distributed manner, while the number of accelerometers and conventional strain gauges on each face is three. The excitations included the sine, sine-sweep and the Niigata earthquake excitations. The changes of the structural dynamic characteristics of the columns due to excitations and progressive damages were investigated based on the general principle that

vibration measurements prior to and after a damage scenarios should give information damage occurrence. The performances of the sensors for structural identification are also comparatively discussed.

7647-57, Session 7a

Detection and assessment of wood decay in glulam beams using a decay rate approach

H. L. Reis, A. Senalik, Univ. of Illinois at Urbana-Champaign (United States); F. C. Beall, Univ. of California, Berkeley (United States)

A glulam beam retired from the field and without visible indications of wood decay was used. Towards detection and assessing wood decay, X-ray computer tomography and ultrasonic measurements were carried out. It was observed that decrease in mass density with increasing levels of wood decay affects x-rays attenuation and allows radioscopy to detect and assess wood decay. To detect and assess decay when only one lateral side of the beam is available, a modified impulse-echo is presented. The modified impulse-echo approach is based on observing the dynamic response of each lamina in the glulam beam to the drop of a steel sphere onto a steel plate coupled to the glulam beam lamina and upon a decay rate analysis of the corresponding time domain signal in a frequency band of interest. The selection of the frequency band of interest only requires knowledge of the nominal transverse dimensions of each lamina in the beam and of the corresponding wood species. It was observed that decay rate analysis allows detection and assessment of wood decay. The decay rate approach leads to a 5.7% probability of false negative calls (i.e., decayed wood assumed to be sound wood) and to a 3.5% probability of false positive calls (i.e., sound wood assumed to be decayed), with an overall rate of false calls of 7.2%. Considering the variability that exists in wood including the presence of splits, orientation and thickness of growth rings, etc., this relative low rate of false calls makes this approach very attractive. Results show that results from both X-ray computer tomography and impulse-echo decay-rated based measurements are consistent with each other and can be used to detect and assess wood decay in structural lumber.

7647-58, Session 7b

* An emerging time-domain sensing technique for large scale, multi-function fiber optic sensor networks

C. Wang, C. Herath, Mississippi State Univ. (United States)

Power losses, light intensity fluctuations, and high terminal equipment costs are important issues in development of a large scale, multi-function fiber optic sensor systems or sensor networks. Fiber loop ringdown (FLRD), a uniform time-domain sensing scheme, has potential to help address the three key issues in the development of fiber optic sensor networks for simultaneously sensing multiple quantities, including pressure, temperature, strain, chemical species, etc. with fast response, high sensitivity, and significantly reduced costs. Performance and design of a cluster of individual FLRD-based fiber optic sensors for pressure, force, temperature, strain, chemical compounds, etc. are presented. Multiplexing those individual FLRD sensor units into a large scale sensor system for multi-function sensing is proposed. System configuration, operation, and advantages compared with the peer-sensors based on current sensing schemes are discussed.

7647-59, Session 7b

Noise effects on mobile sensor platform localization

N. Chopra, B. Balachandran, Univ. of Maryland, College Park (United States); H. Karki, The Petroleum Institute (United Arab Emirates)

The problem of estimating the configuration of a robotic system relative to a known (static or dynamic) environment is known as robot localization. Several algorithms for localizing robotic systems have been developed in the literature, for example, the Extended Kalman Filter localization (EKF) algorithm. These algorithms use noisy sensor data to estimate the relative position and configuration of the robot with respect to the surrounding environment. In this article, the effect of different levels of sensor noise on the performance of several localization algorithms is studied and relevance of this work to the use of mobile sensor platforms in applications such as oil storage tanks is discussed.

7647-60, Session 7b

Systematic decision-support in damage assessment: an evidential reasoning approach

I. Lopez, N. Sarigul-Klijn, Univ. of California, Davis (United States)

In real-world applications, sensory data is often incomplete and imprecise. Structural health monitoring is an information-based engineering application that is a data and knowledge intensive application with unique requirements from engineering information modeling. Due to structural complexity and rich semantic requirements, damage assessment analysis needs to incorporate modeling of imprecise and uncertain information. Structural sensory data is subject to random disturbances, and the environment in which structural system operates is often precisely unpredictable. We develop an expert supervisory strategy based on evidential reasoning to deal with uncertain decision knowledge in multi-attribute decision-making with both quantitative and qualitative information sources. In this paper, we begin by showing that a Dempster-Shafer inference learning system can be used to adapt nominal damage assessment system to compensate for data uncertainty. In addition, we show that the performance in damage assessment can be significantly enhanced by exploiting damage detection and identification information to achieve an “adaptive” damage assessment approach depending on the type of damage that occurred. The robustness of the damage detection approach to uncertainty in the input data is investigated using probabilistic-based confidence bounds of prediction accuracy. This approach is illustrated with publicly available fault detection datasets and laboratory experiments.

7647-61, Session 7b

* Intelligent fault detection, diagnosis and prevention (iFDDP) technology for the design of smart outlets in healthy and safe homes

I. M. Kao, Stony Brook Univ. (United States)

In the paper, we will present the ongoing study to significantly reduce various types of electrical fire and injury hazards at home by developing a smart outlet, using innovative sensors and sensing system with an intelligent fault detection, diagnosis, and prevention (iFDDP) technology. This study can improve a very important device of our existing infrastructure in our daily lives, and provide a better quality of life for all. In this paper, we will present the study from the perspectives of mechanisms, sensing, fingerprints, diagnosis, and prevention of serial arcing, a very common but serious safety hazard to homes. A fingerprint study with pattern recognition of the serial arcing on experimental results has been conducted by examining the wavelet components. The analysis indicates that typical “W” or “M” fingerprints are recurring when the high-frequency serial arcing takes place in the detailed components of wavelet. Such characteristics occur at the transition of the intermittent electrical connection through arcing. Experimental data also suggest that such arcing will increase the temperature rapidly, causing degradation in the outlet and further aggravating the condition. The integrated sensor and sensing system

with signal analysis will also be presented. Another benefit of the ongoing research study is the capacity of real-time monitoring of the energy use of individual appliances to save energy and power usage. The new iFDDP technology can potentially revolutionize the usage of outlets in homes and provide a healthy and safe home environment for better quality of life.

7647-62, Session 7b

Object identification by multispectral fusion and Haar classification

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An approach to identify and classify objects in real time by multispectral imaging, image registration, wavelets based fusion, and Haar classification is presented. The specific object of interest is a cardboard box placed on the roadside. The proposed approach involves capturing a scene in the visible and infra red spectrum. Fusing the spectra is performed by using the wavelet transform after the images are spatially registered. Further, Haar training is performed using sample positives and negatives prior to classification. The presented approach is tested to work in real time with very good accuracy. If successful, the method will be applied to the detection of a variety of anomalous objects placed at the roadside.

7647-63, Session 7b

A survey of the reduction of uncertainties by comprehensive monitoring of load-carrying structures

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Long Abstract:

During the design process of a load-carrying structure, the real operational loads are unknown in most times. Thus, the loads to estimate the durability during design are taken from experiences with calculations, numerical simulations or real experiments. However, even an experiment represents just a partial cutout of all possible load scenarios. In contrast, monitoring systems offer the possibility to measure and reconstruct loads and vibra-tions during the usage of any structure out in the field. What is more, those measurements are influenced by uncertainties such as measure- or system-noise, signals from misplaced sensors, fatigue of sensors or changes in system dynamics.

Today, current methods analyse the dynamics and damages of load-carrying structures. For example, with the Finite Element Analysis (FEA) static and dynamic behaviour of structures could be calculated. Usage-Monitoring-Systems offer information about loads and vibrations, Structural Health Monitoring (SHM) show position and size of damages. With methods of damage accumulation we can calculate the level of fatigue [4, 5, 7].

The monitoring method presented in this paper combines these methods to a compre-hensive monitoring system which is represented in an information processing chain. Sev-eral influences of uncertainty that affect the quality of state identification are analyzed, figure 1. Stochastic signal processing is used to reduce the effects of probabilistic influences, adaptive filtering allows observing changes in system parameters within time. Those changes can be used to update the model parameters online [6]

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Numerical simulations of a simple beam are performed to verify the applicability and accuracy of the proposed methods, figure 2.

The simulation of the dynamic responses is conducted with a high order model. For the reduced number Nred DOF measured signals are simulated. Here, those signals are super-posed with a white noise signal and are used for reconstruction of the full dynamic state of the structure. The influence of different uncertainties or disturbances like measurement noise, low order of considered modes or variance of sensor position to the accuracy of the reconstruction is examined and compared with each other. As a quality criterion for efficiency of filtering and to evaluate uncertainties, the mean square error and the coherence of simulated and reconstructed vibration and loads is used.

This work shows that uncertainties in any load-carrying system can be reduced when knowing the real load condition of the system as well as any possible disturbances any-time and anywhere during its lifetime.

7647-156, Poster Session

Mechanical monolithic tiltmeter for low frequency measurements

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The paper describes the application of a monolithic folded pendulum (FP) as a tiltmeter for geophysical applications, developed at the University of Salerno. Both the theoretical model and the experimental results of a tunable mechanical monolithic FP tiltmeter prototype are presented and discussed. Some of the most important characteristics, like the possibility of tuning its resonance frequency to values as low as 70 mHz and its measured resolution of 0.1 nrad at 100 mHz, are detailed. Among the scientific results, earth tilt tides have been already observed with a monolithic FP tiltmeter prototype.

7647-157, Poster Session

Low frequency seismic noise acquisition and analysis in the Homestake Mine with tunable monolithic horizontal sensors

F. Acernese, Univ. degli Studi di Salerno (Italy); R. De Rosa, Univ. degli Studi di Napoli Federico II (Italy); R. DeSalvo, Califonia Institute of Technology (United States); G. Giordano, Univ. degli Studi di Salerno (Italy); J. Harms, V. Mandic, Univ. of Minnesota, Twin Cities (United States); F. Barone, Istituto Nazionale di Fisica Nucleare (Italy)

In this paper we describe the scientific data recorded along one month of data taking of two mechanical monolithic horizontal sensor prototypes located in a blind-ended (side) tunnel 2000 ft deep in the Homestake (South Dakota, USA) mine chosen to host the Deep Underground Science and Engineering Laboratory (DUSEL). The two mechanical monolithic sensors, developed at the University of Salerno, are placed, in thermally insulating enclosures, onto concrete slabs connected to the bedrock, and behind a sound-proofing wall. The main goal of this experiment is to characterize the Homestake site in the frequency band 10^-4 - 30 Hz and to estimate the level of Newtonian noise, providing also the necessary preliminary information to understand the feasibility of underground gravitational-wave interferometers sensitive at 1 Hz and below.

7647-159, Poster Session

Study on the fatigue reliability of optical fiber based on distributed optical fiber strain sensing technique

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It is significant to improve the fatigue reliability of strain measurement

for damage identification of important civil infrastructures bearing long-term fatigue loads, such as bridges and prestressed steel structures. In this paper, based on the distributed optical fiber strain sensing technique of pulse-prepump Brillouin Optical Time Domain Analysis(PPP-BOTDA), three types of optical fiber, i.e. single-mode optical fiber with Jacket (Type-A), UV resin-coated optical fiber (Type-B) and optical fiber with improved strain sensitivity (Type-C), were selected to study on the monitoring reliability in low cycle fatigue experiment with different initial strain and amplitudes. Three kinds of optical fibers were tested in direct tension at certain cycle numbers. Initial experimental results show that the strains of the Type-A and Type-B drift more with cycle numbers, while the Type-C show little deviation with the true value. It is indicated that the monitoring data of Type-A and Type-B was not reliable with fatigue loading, because of the fatigue damage accumulation of the optical fiber, while there is little effect in Type-C. As a result, optical fibers with improved strain sensitivity can be used in the long-term monitoring of important structures bearing long-term fatigue loads such as bridges and prestressed steel structures.

7647-160, Poster Session

Structural health monitoring of a composite wind turbine blade using fiber Bragg grating sensors

H. Bang, H. Shin, Y. Ju, Korea Institute of Energy Research (Korea, Republic of)

This paper describes implementation of FBG (fiber Bragg grating) sensors to monitor the composite manufacturing process as well as load bearing condition of down scaled 3.5m wind turbine rotor blade.

At first, wavelength division multiplexed 5 point FBG sensors were embedded between the unidirectional layer of carbon spar and we measured the internal strain during oven curing process. We made blade skin with glass fiber materials by resin infusion molding process in air temperature, and the box spar structures were made by oven curing process using carbon fiber prepreg. Because the unwanted residual compressive strain can cause early delaminations between the glass skin and carbon spar, the residual strain level in the carbon is need to be known after the high temperature oven curing process.

After the monitoring the manufacturing process, these embedded FBG sensors were used to measure the strain condition of the blade in structural performance tests. Impact modal tests and flap and edgewise static tests were performed using 5 FBG sensors. In the modal tests, we made a comparative study of FBG test result with that of conventional accelerometers and FE analysis. In the static load test, measured strain result of electric strain gage and FBGs were compared.

7647-161, Poster Session

Adaptive optics system for fast automatic control of laser beam jitters in air

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In this paper we present an Adaptive Optics (AO) System properly developed for the fast automatic control of laser beam jitters on first and second order Hermite Gauss (HG) modes. This research has been driven by the necessity of suppressing laser beam geometrical fluctuations in the interferometric Gravitational Waves (GW) antennas. In fact, it is demonstrated that oscillations of higher order Hermite Gauss modes in the laser source couple with the interferometer asymmetries and give rise to additional noise that limits the antenna sensitivity below the value of 10^-23 1/sqrt(Hz) . In the paper we demonstrate the feasibility of a novel AO System performing effective laser jitters suppression in the bandwidth up to 200 Hz. In particular we describe an innovative AO System that extracts error signals as HG coefficients and then corrects the wavefront through driver commands sent to the deformable mirror in terms of Zernike profiles. We have implemented and tested an experimental Prototype of the AO System in our laboratory at the University of Salerno. The results confirm effectiveness and robustness of the control which performs significant reduction of the first and second order laser beam geometrical fluctuations. In particular we have measured the decrease of astigmatism and defocus modes of 60 dB at low frequency below 1 Hz and of 20 dB up to 200 Hz, which at the best of the present technology fulfils the requirements for noise reduction of the interferometric GW detectors.

7647-162, Poster Session

Piezoelectric sensor system for simultaneous detection of local and global damages in structures

Y. Roh, H. Kwon, J. Kim, B. Kim, Kyungpook National Univ. (Korea, Republic of)

This paper presents the feasibility of a sensor system consisting of piezoelectric oscillator sensors to detect local damages and ultrasonic sensors to detect global damages in a structure. The oscillator sensor is composed of a feedback oscillator circuit and a piezoceramic lateral mode vibrator to be attached to a structure. Damage to the structure causes a change in the resonant frequency of the vibrator. The oscillator circuit instantly detects the frequency change and configures the damages. However, the response of the oscillator sensor is limited to the area around the sensor, thus local measurement. The ultrasonic sensor generates Lamb waves and the waves traveled over a long distance are received by the piezoceramic patch used in the oscillator. The received wave form reflects all the defects encountered during the propagation, thus global measurement is possible. The two sensor types are combined as a sensor network, and its operation system is developed as a portable unit for practical applicability. Performance of the sensor system was verified with a sample aluminum plate where artificial cracks of different lengths and number were imposed in sequence. Performance of the sensor was quite promising, responding accurately and reliably to the crack configuration.

7647-163, Poster Session

Development of NDT system with image reconstruction capabilities of flaws using EMAT

Y. Nishimura, A. Sasamoto, T. Suzuki, National Institute of Advanced Industrial Science and Technology (Japan)

EMAT which is based on magnetostrictive effects was employed to detect internal flaws in an inspected sample with surface oxide scaling. EMAT is a contact-free NDT method and can quickly scan over the inspected sample's surface. It is also more suitable for rough surfaces of inspected samples than conventional piezo-elastic transducers. This study seeks to derive internal 3D-images of sample. As a target sample, chromium molybdenum steel (SCM415) was annealed at 600 ℃ to 900℃ for two to eight hours and subjected to EMAT to survey its signal properties. The sample annealed at 875 ℃ for two hours produced clear EMAT signals good enough to recognize internal flaws. The data derived from these samples were compared to data from an actually used sample. The EMAT signal derived from the actual sample was found too noisy to detect and identify internal flaws and to reconstruct flaw images in a computer. The noise was thought to come from the Barkhausen effect and can easily be removed from the inspected samples by averaging EMAT signals. However, it is impossible to average EMAT signals while quickly scanning a sample's surface. There is another method to remove noise from EMAT signal. Because the frequency of Barkhousen (BH) noise is much higher than the EMAT's resonance frequency, most of BH noise can be removed numerically by a low-pass filter but such a low-pass such a filter produces its own noise. This study proposes to remove the noise

by maximizing the likelihood of signals including BH noise in all the sampled signals based on the probability distribution of BH noise. To derive 3D internal images of sample, a high-speed 3D-scanner driven by linear motors with a positioning precision of 0.5 for each directions (x, y, z) and having a scanning speed of 1m/s was developed. A time series of data consisting of 16,000 samples for each position, was sampled by an A/D converter (400MHz) at 1024x1024 positions within a 5cmx5cm area. The signals were subjected to Hilbert transformation to derive curve envelopes that coincide with the distribution of a reflection coefficient in the inspected sample. The time series of data was arranged in each scanning line meaning (X direction), and 3D internal-images of the sample were successfully reconstructed and depicted.

7647-164, Poster Session

Oblique excitation of nearly-longitudinal waves in thick plates

Y. Ying, J. H. Garrett, Jr., D. W. Greve, I. J. Oppenheim, L. Soibelman, Carnegie Mellon Univ. (United States)

Previous research has studied the generation of nearly-longitudinal waves in thick plates by edge excitation at relatively high frequency-thickness products. These nearly-longitudinal waves, also well known as trailing pulses, are promising for flaw detection due to their shorter wavelength and the capability of retaining the pulse characteristics after scattering from defects. However, in the real world, the edges of the structures may not be accessible due to construction design or environmental constraints. Therefore, we propose to excite ultrasonic waves with a wedge transducer in oblique incidence at the plate surface. We use finite element simulations to examine the generation of nearly-longitudinal waves in a thick plate. Experiments are conducted to validate this wave behavior when a wedge transducer is applied. The good agreement between the simulation and experiments shows that uniformly spaced trailing pulses, with the initial arrival traveling at the speed of a longitudinal bulk wave, are produced in a thick plate by wedge excitation. The received signals, however, are weaker than those when an edge-mounted transducer is used. In this paper, we theoretically investigate the dependency of the strength of nearly-longitudinal waves on the incidence angle to choose optimal wedge angle for energy transmission. Consistent simulations and experimental results are presented. Furthermore, we employ the nearly-longitudinal waves excited by a wedge transducer for flaw detection. The correspondence among theory, simulation and experiment demonstrate that nearly-longitudinal waves by oblique incidence excitation are a good alternative for infrastructure inspection, especially for plates permitting only surface access.

7647-165, Poster Session

The development and performance study of polypropylene packaged FBG strain sensor for monitoring on asphalt pavement

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Modulus of asphalt concrete is very low, so ordinary FRP or Steel packaged sensors can not measure its strain accurately. In view of this problem, one kind of optical fiber Bragg sensor based on polypropylene, one kind of thermoplastic resin, was proposed in this article. Firstly, a conveniently installed and dissembled steel die was designed and fabricated. Then, after characteristics study of polypropylene during heating and repeatedly tries, a reliable grouting technique was formed. After this, real-time monitor of the entire sensor packaging process was performed with demodulator, and then the sensor mechanics performance, the microscopic structure and properties were studied thoroughly. Results of SEM indicate that interface of optical fiber and polypropylene is considerable tight. Measured strain during sensor making is reasonable. Then, the FBG sensors were buried into concrete columns to measure their strain during continuously 7 day-long early-times solidification and compression test. Also, the FBG sensors were used to measure strain of asphalt concrete beams. Linearity and repeatability of the sensors are quit well and measured strains are quite believable. So, we can say that due to bond and deformation compatibility between packaged material and FBG, FBG sensor and measured material, especially low modulus of packaging materials, strain of asphalt pavement can be monitored by the kind of sensors.

7647-166, Poster Session

Decentralized semi-active structural control system with wireless sensing and control network

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Decentralized Semi-active Structural Control System with Wireless Sensing and Control Network

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ABSTRACT

In the past decades, structural control technologies have received great attention for hazard mitigation; however, traditional structural control techniques are centralized in nature. As structural control systems grow in size, there are many problems with the centralized control architectures. Recently, a novel decentralized structural control method based on substructure and LQG control algorithm has been proposed by the authors. The decentralized control algorithm is suitable for implementation on a control system of densely distributed sensors and actuators. In this paper, application of this method with experimental verification by a new sensing and control network developed by the authors is studied. The sensor and control network consists of active sensing units in which actuation interface is to allow commanding semi-active variable dampers in a structural control system. The decentralized control algorithm is embedded into the computational core of each active sensing unit. A large size structure is divided into substructures. The distributed active sensing units in a substructure are grouped into a cluster to collect measurements, transmit data with wireless communication, determines control forces using computational resource, and command structural actuators at a specified time interval, all in real-time. Therefore, structural control can be performed by local controllers in different substructures concurrently with parallel computing or even independently. Considering the practical case that measurements at the substructure interface are not available, active sensing units in a substructure needs to communicate with limited information with those in the surrounding substructures. To assess its efficacy in practice, the proposed technique is experimentally verified by application to decentralized semi-active control of a 6-story steel-frame building using MR dampers. The building is excited at its base by shaking table, two MR dampers are located on the first and the fourth floor, and limited accelerometers are installed. By evaluating the control performance, the feasibility of the decentralized wireless sensing and control network is discussed.

Keywords: decentralized structural control; wireless sensing and control network; LQG control algorithm; Semi-active control, MR-damper

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7647-167, Poster Session

An optimal design of magnetostrictive material (MsM) based energy harvester

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Conf. 7647: Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems

The objective of this research is to design an optimized energy harvesting system based on a magnetostrictive material (MsM) to power the Wireless Intelligent Sensor Platform (WISP), developed by North Carolina State University. Compared to the piezoelectric material based harvester, MsM is more flexible, has an inherent low resonance frequency, and it provides almost unlimited number of vibration cycles. Without a dense mass, the cantilever beam with two Metglas 2605SA1 (cast) layers laminated on a steel substrate has the first order resonance frequency lower than 70Hz. Several important considerations in designing the optimal MsM generator are explored, including the coil and cantilever beam optimization, load matching, and efficiency. The coil and the geometry of the MsM cantilever beam are optimized to maximize the output power using MATLAB Sequential Quadratic Programming method under the constraint that the whole device size including the coil is 1cm3. From the measurement, the open circuit voltage is 1.26V when the MsM device is working at the 2nd order resonance frequency 342Hz. The output power is 1.2mW. An optimized energy harvesting circuit for maximum power transfer from a Magnetostrictive Material (MsM) vibration generator has also been designed. Since the MsM device has low open circuit output voltage characteristics, a full-wave quadrupler was designed to boost the rectified output voltage because of its better load regulation, lower ripple and faster settling time. To implement complex conjugate impedance matching, a discontinuous conduction mode (DCM) buck-boost converter was designed to charge a rechargeable battery. Compared to the previous work done by Lei Wang, at least 2 times higher power is obtained at a lower frequency with a lower coupling coefficient MsM material. The power density is 4 times higher than the work done by Lei Wang using his power density calculation method.

7647-168, Poster Session

Coupling of ab-initio and bifurcation techniques for martensitic transformations in transition-metal materials

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The technologically important properties of transition-metal materials such as shape memory alloys (SMAs) and magnetic SMAs (MSMAs) are due to solid-to-solid martensitic phase transformations (MPTs) which result from an instability of the material's crystalline structure. Ab-initio simulations are currently capable of providing accurate predictions of material behavior, but methods such as molecular dynamics or monte carlo simulation are computationally too expensive to comprehensively explore a material's MPT behavior.

This work aims to couple a state-of-the-art electronic density functional theory (DFT) software package capable of ab-initio predictions of materials behavior with a branch-following and bifurcation (BFB) software package capable of efficiently and comprehensively mapping out the MPTs exhibited by any given material. BFB techniques map out a curve or branch corresponding to the evolution of a material's equilibrium configurations as a parameter (such as temperature or applied magnetic field) is varied. Following the natural evolution of the material's behavior allows for significant computational savings over other methods. Often the branches of two different crystalline structures cross. The point of intersection is called a bifurcation point. These bifurcation points allow for the systematic discovery and exploration of many material phases.

The coupled DFT-BFB computational system will be described and its features demonstrated for some simple materials of interest. The results indicate that DFT simulations coupled with BFB techniques have the potential to provide new insights on why certain materials exhibit technologically useful MPTs and others do not.

7647-169, Poster Session

In-situ geo-characterization using wireless functional signals

X. Li, T. S. Yun, L. Cheng, S. Pamukcu, Lehigh Univ. (United States)

The effective in-situ characterization and hazard monitoring in geo-engineering practice are key issues that can be addressed by use of wireless sensor networks. The conventional methods deployed in geo-engineering practice for in-situ characterization experience limitations in acquisition of spatially localized and/or temporally discrete data. We propose the idea of functional signal that address such limitations. The concept of functional signal advocates that the variation of the link quality between wireless transceivers can be used as an effective sensing mechanism which reflects characteristics of geo-media subjected to various geo-events. This novel method makes a wireless signal network as a global geo-media measurement system that performs the geotechnical characterization in a spatial and temporal continuous fashion with embedded wireless sensors in distributed configurations. This not only enables to evaluate and visualize entire geo-system but also helps develop knowledge of functional-signal map to benchmark such continuums through spatiotemporal calibrations of wireless link quality. Simulation and experiment results show that this new idea can provide simple and robust sensing methodology to identify and evaluate indiscriminate geo-events and evolution of geophysical conditions in geo-media.

7647-170, Poster Session

Low-cost self-cleaning room temperature tin dioxide thin film gas sensor on polymer nanostructures

M. Shen, H. Huo, F. Yan, C. Wang, H. Ren, Univ. of Massachusetts Lowell (United States)

We have successfully fabricated tin dioxide (SnO2) thin film CO gas sensors on nanospiked polyurethane (PU) polymer surfaces that are replicated with a low-cost soft nanolithography method from nanospiked silicon surfaces formed with femtosecond laser irradiations. The sensors show sensitive responses to the CO gas at room temperature because of the high area/volume ratio and sharp structures of the nanospikes. This is much different from the sensors of SnO2 thin film coated on smooth surfaces that show no response to the CO gas at room temperature; the operating temperatures of the sensors must be above 150 degree C. To make the nanostructure sensor surface behave self-cleaning like lotus leaves, we deposited a silane monolayer on the surface of the SnO2 thin film sensors in a vacuum chamber with the 1H,1H,2H,2H-perfluorooctyltrichlorosilane (PFOTS). The contact angle measurement conducted on the PFOTS monolayer-coated SnO2 gas sensors indicates that a super-hydrophobic surface formed on the nanospike sensor. The CO gas response sensitivity of the PFOTS-coated SnO2 sensors is almost the same to that of the as-fabricated SnO2 sensors without the PFOTS coating. Such a super-hydrophobic surface can protect the sensors exposed to moisture and heavy particulates, and can perform cleaning-in-place operations to prolong the lifetime of the sensors. These results show a great potential to fabricate thousands of identical gas sensors at low cost. The identical gas sensors also decrease the calibration cost greatly. In addition, the sensors operating at room temperature greatly decreases the electrical power consumption of the sensors.

7647-171, Poster Session

Classification of damage in structural systems using time series analysis and supervised and unsupervised pattern recognition techniques

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Developed for studying long, periodic records of various measured quantities, time series analysis methods are inherently suited and offer interesting possibilities for Structural Health Monitoring (SHM)

applications. However, their use in SHM can still be regarded as an emerging application and deserves more studies. In this research, Autoregressive (AR) models were used to fit experimental acceleration time histories from two structural systems, a 3-storey bookshelf-type laboratory structure and the ASCE Phase II SHM Benchmark Structure, in healthy and several damaged states. The coefficients of the AR models were chosen as damage sensitive features. Preliminary visual inspection of the large sets of AR coefficients to check the presence of clusters corresponding to different damage severities was achieved using Sammon mapping - an efficient nonlinear data compression technique. Systematic classification of damage into states based on the analysis of the AR coefficients was achieved using three supervised classification techniques: Back-Propagation Neural Networks (BP-ANNs) Nearest Neighbour Classification (NNC) and Learning Vector Quantisation (LVQ), and one unsupervised technique: Self-Organising Maps (SOM). This paper discusses the performance of AR coefficients as damage sensitive features and compares the efficiency of the four classification techniques using experimental data.

7647-64, Session 8a

Detecting seismic response signals using singular spectrum analysis

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Singular Spectrum Analysis (SSA) is a novel non-parametric technique based on principle of multivariate statistics. The original time series is decomposed into a number of additive time series, each of which can be easily identified as being part of the modulated signals, or as being part of the random noise. It provides trend extraction involves a decomposition of a time series into low-frequency trends and high-frequency variability. It shows that the embedding dimension m of a dynamical time series can be conducted by the Singular Value Decomposition (SVD) experiments. This SVD scheme was used to detect low-dimensionally dynamic signals and the residuals. In this study SSA and nonlinear identification are used to measure the nonlinear seismic responses of reinforced concrete structures and to elucidate residual deformation. Then, damage feature extraction is conducted using the high-frequency variability of SSA, the Holder exponent and the Level-1 detail of the discrete wavelet component. Five reinforced concrete frame test data collected in response to various degrees of seismic excitation are used to study the severity of damage.

7647-65, Session 8a

* Support vector machine for abnormality detection of a cable-stayed bridge

D. M. Vines-Cavanaugh, Y. Cao, M. L. Wang, Northeastern Univ. (United States)

The Support Vector Machine (SVM) is an algorithm used for solving data classification problems. It is a machine learning technique, and therefore, rather than having an explicit methodology, it relies on learning how to classify data from examples given in a training process. This characteristic is highly beneficial as it allows the SVM to have broad applications ranging from image recognition to leukemia diagnosis. The focus of this paper is on the SVMs application to the field of structural health monitoring; specifically, its use in detecting structural abnormalities from a cable-stayed bridge's health monitoring system (HMS) data. An inherent complexity of this application is the acquiring of training data, representing structural abnormalities, from a structure that is unable to be damaged. Accordingly, this issue is resolved by developing a finite element model and using it to simulate each abnormality that is to be detected. Regarding the application's success, this paper compares SVM results to those from another, more established, health monitoring technique. In accomplishing this, the SVM is tested to see that it can detect some abnormal expansion joint behavior, 10-20% fixity in the longitudinal direction, that was previously found using a finite element updating technique.

7647-66, Session 8a

Adaptive noise variance identification for data fusion using subspace-based technique

Z. Li, C. Chang, Hong Kong Univ. of Science and Technology (Hong Kong, China)

Displacement response of civil structures is of great importance for condition monitoring and evaluation of these structures. Current displacement measurement techniques such as the global positioning system and the image-based approach however suffer from low sampling rate as well as measurement noise. To circumvent these problems, the Kalman filter is commonly employed to fuse displacement measurement with acceleration which can be easily and accurately obtained. Although the Kalman filter can mitigate the aforementioned limitations, the performance of data fusion however depends on the accurate estimation of noise variances in the displacement and acceleration measurement. Typically, noise variances are estimated empirically a priori and are assumed to be invariant throughout the fusion which may lead to large estimation error. In this study, an adaptive subspace-based technique is developed to identify time-varying noise variances in the measured response. The proposed method estimates the variances of acceleration and displacement independently and can ensure the positive definite of noise variances. Furthermore, the proposed technique can be performed in on-line fashion; hence, it can be incorporated into an adaptive Kalman filter. A numerical example and a laboratory test are conducted to validate the proposed approach

7647-67, Session 8b

* Design and fabrication of a sensor integrated MEMS/nano-skin system for human physiological response measurement

Y. Lin, Northeastern Univ. (United States)

Human state in human-machine systems highly affects the system performance. Human state should be monitored to enhance human-machine interaction, optimize the system performance, and derive the accident risk and cost. After literature review, this study revealed that physiological cues are suitable for monitoring human state in human-machine system. This study was focused on developing a new sensing system, i.e. MEMS/Nano-Skin, to non-intrusively measure physiological cues at human-machine contact surfaces, and then assess human state in human-machine systems.

The first part was to analyze the characteristics of human-machine contact, and find the appropriate physiological cues for monitoring human state. Human-machine contact usually happen between human skin and machines, and is dynamic. Generally, heart rate, skin conductance, skin temperature, gripping force, blood alcohol concentration, sweat rate, and electromyography have close relation with human state. These physiological cues can be measured from human skin to evaluate human state in human-machine systems. The measurement of physiological cues does not add constrains to humans, does not affect human normal state, and is non-intrusive. The non-intrusive measurement of physiological cues is essential to find the real reason for the change of human state in human-machine systems, and then activate appropriate response of machines.

The second part was to select appropriate sensing methods to measure the human physiological cues from the human-machine contact surfaces. The physiological signals are weak, and should be acquired using sensors with high sensitivity. Due to the dynamic human-machine contact, the physiological signals may be discontinuous. A sensor network will cover the human-machine contact surfaces to measure physiological cues, and ensure the consistence and continuity of measurement. The sensor network needs sensors with small sizes and low energy-consumption. This study reviewed and compared the common sensors, MEMS sensors, and NANO sensors. It was found that MEMS sensors and NANO sensors can achieve higher

sensitivity, smaller sizes, and lower energy-consumption than common sensors. Both of them can offer unique contributions to human-machine contact based non-intrusive measurement of physiological cues.

The third part was to discuss the design and manufacture of MEMS/Nano-Skin system. The system generally involves four components, the flexible substrate, sensors, special integrated circuit, and connecting circuits between sensors and special integrated circuit. The flexible substrate is used to fix the sensors, special integrated circuit, and connecting circuits between them, and protect them. The functions of special integrated circuit include power supply to sensors, signal acquisition, signal conditioning, and signal transmission. The connecting circuits between sensors and special integrated circuit consist of two networks, one network for power supply to sensors and another network for signal acquisition. The MEMS/Nano-Skin is flexible, and can be attached to any curved surfaces of machines. Except the special integrated circuit, this study investigated the manufacture of the flexible substrate with sensors and connecting circuits.

After a prototype MEMS/Nano-Skin was produced using MEMS and NANO technologies, experiments were designed to verify the measurement accuracy in human physiological responses. It is feasible to use this MEMS/Nano-Skin to measure physiological cues from human-machine contact surfaces to monitor human state in human-machine interactions.

7647-68, Session 8b

Carbon nanotube sensors on CMOS circuitry for environmental monitoring

Y. Liu, C. Chen, M. R. Dokmeci, M. L. Wang, Northeastern Univ. (United States)

Single-walled carbon nanotubes (SWNTs) with their large surface area, high aspect ratio are one of the novel materials which have numerous attractive features amenable for high sensitivity sensors. Several nanotube based sensors including, gas, chemical and biosensors have been demonstrated. Moreover, most of these sensors require off chip components to detect the variations in the signals making them complicated and hard to commercialize. Here we present a novel complementary metal oxide semiconductor (CMOS) integrated carbon nanotube sensors for portable high sensitivity chemical sensing applications. Multiple zincation steps have been developed to axcertain proper electrical and mechanical connectivity between the carbon nanotubes and the foundry made CMOS circuitry. The SWNTs have been integrated onto (CMOS) circuitry as the feedback resistor of a Miller compensated operational amplifier utilizing low temperature Dielectrophoretic (DEP) assembly process which has been tailored to be compatible with the post-CMOS integration at the die level. Building nanotube sensors directly on commercial CMOS circuitry allows single chip solutions eliminating the need for long parasitic lines and numerous wire bonds. The carbon nanotube sensors realized on CMOS circuitry strong response to various vapors including methanol and dinitrotoluene. The remarkable set of attributes of the SWNTs realized on CMOS electronics chips provides an attractive platform for high sensitivity portable nanotube based bio and chemical sensors.

7647-69, Session 8b

Reconfigurable multivariable MEMS sensor array

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Research into operational aspects of mini unmanned aerial vehicles (UAV) and structural health monitoring systems (SHM) is being conducted at the Defence Science and Technology Organisation and La Trobe University. A fundamental area of interest is investigating the problems associated with miniaturisation of the control and health monitoring sensors for such systems.

While many technologies for UAV and SHM systems can be, and have been, adapted from those currently available in large manned aircraft; cost, weight, and size constraints have prevented mini UAVs from including many of the robustness mechanisms common to larger aircraft. Moreover, the ubiquitous nature of the sensing requirements for SHM systems has limited their uptake, due mainly to the same issues of cost, weight and size.

This paper details the design of a reconfigurable multivariable MEMS (Micro Electro Mechanical System) array to address these issues. This array is comprised of multiple instances of identical sensors, which can be dynamically reconfigured to achieve the desired measurand(s) with tradeoffs against accuracy. The available measurands include such items as; accelerations, rotational rates, magnetic fields (all in X, Y and Z directions), temperature and pressure. The full paper will present the design of a reconfigurable multivariable MEMS sensor array together with simulation and measured results.

7647-70, Session 9a

Steel bridge fatigue crack detection with piezoelectric wafer active sensors

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Piezoelectric wafer active sensors (PWAS) are well known for its dual capabilities in structural health monitoring, acting as either actuators or sensors. Due to the variety of deterioration sources and locations of bridge defects, there is currently no single method that can detect and address the potential sources globally. In our research, our goal of the PWAS based sensing has the novelty of implementing both passive (as acoustic emission) and active (as ultrasonic transducers) sensing using a single PWAS network. The combined schematic is using acoustic emission to detect the presence of fatigue cracks in steel bridges in their early stage since methods such as ultrasonics are unable to quantify the initial condition of crack growth since most of the fatigue life for these details is consumed while the fatigue crack is too small to be detected. Hence, combing acoustic emission with ultrasonic active sensing will strengthen the damage detection process. The integration of passive acoustic emission detection with active sensing will be a technological leap forward from the current practice of periodic and subjective visual inspection, and bridge management based primarily on history of past performance.

In this study, extensive laboratory investigation will be performed supported by theoretical modeling analysis. A demonstration system will be presented to show how piezoelectric wafer active sensor is used for acoustic emission. Specimens representing different structures are tested and compared with the finite element model predictions. The results will also be compared with traditional acoustic emission transducers to identify the application barriers.

7647-71, Session 9a

Monitoring concrete by means of embedded sensors and electromechanical impedance technique

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This paper describes the use of embedded and surface bonded piezoelectric transducers PZTs) to monitor concrete by means of the electromechanical impedance (EMI) method. The main objective of the present study is the design and utilization of a rugged and embeddable sensing system capable to monitor curing, stress and damage in concrete structures. Three concrete cylinders with these designed sensors were cast and tested. Surface bonded PZT were also used to compare the response of conventional PZT patch to the response of the embedded system. After the conventional 28-days curing, two cylinders were subjected to a compression test and the third cylinder was subjected to induced damage. The EM signatures were processed

using a statistical index and a slope gradient. The results show that the sensing system and the EMI method are suitable to monitor curing progression and to detect applied stress, damage onset, and damage propagation.

7647-72, Session 9a

Identification of delamination between steel bars and concrete using wavelet packet analysis

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The interface between steel bar and concrete plays an important role in retaining the strength of reinforced concrete under loading. When the interface is damaged, such as crack and de-bond between the two materials, it will lead to significant degradation of the structural performances. In this study, wave propagation on several steel bars embedded in two concrete plates is tested in order to identify the delamination between steel bar and concrete. Piezoelectric actuators and sensors are attached to steel bars for gathering input and response signal. This paper adopts wavelet transform combined with wavelet packet decomposition, component energy and Shannon entropy to analyse the experimental results. Damage features including energy distribution, damage index, entropy distribution and relative entropy are provided. The results demonstrate that both damage index and relative entropy are sensitive to the existence of damage and alter linearly with debonding length in single debonding test, while energy and entropy distribution is largely influenced by the property of the excitation signal. In multiple delaminations test, damage index and relative entropy have no such clear tendency.

7647-73, Session 9a

Monitoring bond performance between steel rebar and concrete by electro-mechanical impedance approach

R. Tawie, H. Lee, Korea Advanced Institute of Science and Technology (Korea, Republic of)

The bond between steel reinforcing bar and concrete is critical to the effectiveness of steel in reinforced concrete structures. The bond strength between the steel rebar and concrete can be evaluated experimentally by pull-out test. It would be very useful to develop a technique to evaluate the bond performance of reinforcing bar in concrete by non-destructive way since pull-out test is labor-intensive and not easy to conduct. In this study, the feasibility of the impedance approach utilizing piezoceramic patches to evaluate bond performance between steel rebar and concrete is investigated. The impedance approach based on the electro-mechanical coupling of piezoelectric materials has been successfully demonstrated by many researchers for detecting damage in structures using high frequency excitations. The test results in the present study show that the bond performance of reinforcing bar is influenced by the quality of concrete. It is apparent that sufficient compaction is important to maximize the bond strength of the reinforcing bar in hardened concrete. In conclusion, this preliminary study shows that it is possible to determine the bond performance of steel rebar in concrete by a non-destructive method based on the electro-mechanical impedance approach.

7647-74, Session 9b

Estimation of fatigue life using electromechanical impedance technique

Y. Y. Lim, C. K. Soh, Nanyang Technological Univ. (Singapore)

Fatigue induced damage is often progressive and gradual in nature. Structures subjected to large number of fatigue load cycles will encounter the process of progressive crack initiation, propagation and finally fracture. Monitoring of structural health, especially for the critical components, is therefore essential for early detection of potential harmful crack. Conventional structural health monitoring (SHM) techniques such as ultrasonic wave propagation technique have been employed to detect incipient crack. Despite the accuracy of crack length measurement offered by these techniques, various drawbacks exist such as the necessity of frequent inspections which are tedious, laborious, potentially hazardous and cost intensive.

Recent advent of smart materials such as piezo-impedance transducer has ushered a new era in the field of SHM. Commonly available techniques such as the electromechanical impedance (EMI) technique and wave propagation technique are well proven to be effective in incipient damage detection and characterization. Exceptional advantages such as autonomous, real-time and online, remote monitoring may provide a cost-effective alternative to the conventional SHM techniques.

In this study, the main focus is to investigate the feasibility of characterizing a propagating fatigue crack in a structure using the EMI technique as well as estimating its remaining fatigue life using the linear elastic fracture mechanics (LEFM) approach. Uniaxial cyclic tensile load is applied on a lab-sized aluminum beam up to failure. Progressive shift in admittance signatures measured by the Piezo-impedance transducer (PZT patch) corresponding to increase of loading cycles reflects effectiveness of the EMI technique in tracing the process of fatigue damage progression. With the use of LEFM, prediction of the remaining life of the structure at different cycles of loading is possible.

7647-75, Session 9b

Life cycle structural health monitoring of airframe structures by strain mapping using FBG sensors

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The purpose of this research is to develop the structural health monitoring system for composite airframe structures by strain mapping through their life cycles. We apply FBG sensor networks to CFRP pressure bulkheads and monitor the strain through their life cycles: molding, processing, assembly, operation and maintenance. Damages, defects and deformations which occurred in each stage are detected using the strain distribution. To establish this SHM system, we worked to develop life cycle monitoring technology and highly reliable diagnostic technology. At first, we monitored the strain of CFRP laminates during molding and processing with FBG sensors. As a result, not only the thermal strain on curing process but also strain changes due to demolding and trimming was measured precisely. In addition, we analyzed the damages and accidental deformation of pressure bulkhead in operation and calculated the strain distributions. On the basis of these results, the location of FBG sensors suitable for the detection of damages and accidental deformation was investigated. Moreover, we developed an optical fiber implementation system using unidirectional prepreg and verified the durability and reliability of the optical fibers with FBG sensors mounted on CFRP by this system. As a result, it was confirmed that the optical fiber sensor system has enough durability and accuracy required for strain monitoring. Furthermore, we developed a small, lightweight optical measurement system suitable for implementation to aircrafts and evaluated its reliability under various temperature conditions.

Conf. 7647: Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems

7647-76, Session 9b

In situ determination of stress intensity factors for the prediction of fatigue crack growth using piezoelectric polymer coatings

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Technical structures like aerofoils, wind energy plants or civil engineering structures are mostly exposed to complex stochastic load configurations. The uncertainty of loading assumptions in connection with complex geometries and joints makes numerical analyses of stresses inaccurate. Thus, concepts of structural health monitoring are valuable means for the assessment of reliability and durability of vulnerable constructions. In particular, fatigue crack growth rates must be estimated in order to determine inspection intervals.

Polyvinylidene fluoride (PVDF) is a transparent elastic polymer exhibiting piezoelectric properties. Connecting the polymer coating to a shell-like structure which is deformed by any kind of loading, electric potential differences are monitored at electrodes applied to the polymer surface at different locations. Solving an inverse problem, stresses acting on the surface of the structure can be calculated from these data.

In a cracked body, stress intensity factors can be calculated from the electrode signals. In contrast to classical procedures using mostly one or two resistance strain gauges applied close to the crack tip, the concept presented in this paper is based on a continuous piezoelectric polymer layer which is applied at the zone of the estimated crack path. A large number of electrodes distributed all over the PVDF coating delivers a variety of signals, which are interpreted to determine Mode-I and II stress intensity factors, T-stresses and the position of the crack tip. These quantities emerge from an inverse optimization problem drawn upon a redundant number of electric signals. Compared to a small number of resistance strain gauges, more signal information is available, the spatial resolution is higher, the location of the crack tip is variable and an external power source is dispensable.

The paper presents theoretical work, analytical calculations and numerical simulations to demonstrate the efficiency of the new sensor concept, to investigate possible design options, to provide the fundamentals for the solution of the inverse problem and to optimize essential parameters.

7647-77, Session 9b

* Continuous piezoelectric health monitoring systems based on ultrasonic guided waves

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Aircraft, the civil, mechanical, power generation and distribution infrastructures are all aging and becoming less reliable. Inspection and off-line nondestructive evaluation are expensive in many ways. Structural health monitoring (SHM) and condition based maintenance (CBM) are keys to shifting the paradigm to cost effective operation and maintenance of reliable systems. A new research project investigates continuous comb transducer strips to generate ultrasonic guided waves for structural health monitoring of plate and shell structures (pipelines, pressure vessels, storage tanks, airframes). A theoretically driven approach, based on the application of wave mechanics principles, is used to research and design a network of strip sensors. Fibrous piezoelectric composites will be considered for the comb elements, widely expanding the design space of these elements to include fiber orientation and volume fraction in addition to size, configuration, and location/size of the electrodes. Piezoelectric and mechanical material properties for these innovative sensor designs will be researched. The system will be capable of active interrogation with Lamb waves upon demand, as well as passive monitoring of acoustic emissions with low power. This paper presents results from wave propagation studies of continuous strip actuators composed of aligned piezoelectric fibers having different orientations with respect to the strip. The results of finite element analyses on the design parameters for a comb transducer strip will be presented.

7647-78, Session 10a

Autonomous smart sensor network for full-scale structural health monitoring

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The demands of aging infrastructure require effective methods for structural monitoring and maintenance. Wireless smart sensor networks offer the ability to enhance structural health monitoring (SHM) practices through the utilization of onboard computation to achieve distributed data management. Such an approach is scalable to the large number of sensor nodes required for high-fidelity modal analysis and damage detection. While much of the technology associated with smart sensors has been available for nearly a decade, the number of full-scale SHM applications has been limited. This slow progress is due, in part, to the complex network management issues that arise when moving from a laboratory setting to a full-scale monitoring implementation. This paper presents flexible network management software that enables continuous and autonomous operation of wireless smart sensor networks for SHM applications. The software components combine sleep/wake cycling for enhanced power management with threshold detection for triggering network wide tasks, such as synchronized sensing or decentralized modal analysis, during periods of critical structural response.

7647-79, Session 10a

Discovery of emerging patterns with immune network theory

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This paper presents an unsupervised structure damage pattern recognition based on the immune network theory. The immune network method provides more flexible learning tools than neural networks and clustering technologies. With a neural network, a network structure has to be defined first, and the network is only as good as its initial design. The immune networks allow their components to change and learn patterns by changing the strength of connections between individual components.

The goal of the presented computational model for unsupervised structure damage pattern recognition is to dynamically construct a network of antibodies (feature vectors) to represent the internal image of the damage patterns presented in the structure. The connection of antibodies depends on the affinity among them. The clonal immune response is initiated by each presented antigenic pattern. The newly generated antibodies with high affinities to the antigen will be recruited into the network. The antibodies with low affinities to the antigen will be eliminated from the network to change affinities of representative antibodies. The continuous recruitment and elimination of antibodies not only provides a competition mechanism to control the survival of antibodies in the network, but also offers great potential to discover and reinforce the beneficial ones, which are able to bind with unpredictable invaders.

The presented immune network-based unsupervised structure damage pattern recognition approach has been validated using a benchmark civil structure. The test result shows the feasibility of using the presented method for the unsupervised structure damage pattern recognition.

7647-80, Session 10a

Multi-functional wireless impedance sensor nodes for structural health monitoring

Conf. 7647: Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems

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This study presents the development of a low cost, but multi-functional wireless sensor node for the impedance-based SHM. The bottom line is to provide multifunctional wireless sensor nodes for excitation/sensing, structural damage detection/sensor self-diagnosis using embedded algorithms, temperature/power monitoring, and energy scavenging. A miniaturized impedance measuring chip is utilized for low cost and low power structural excitation/self-sensing. Then, structural damage detection/sensor self-diagnosis are executed on the on-board microcontroller. Moreover, it can use the harvested power from solar energy to measure and analyze the impedance data. It can also monitor temperature and power consumption. A series of experimental validation studies have been carried out for detecting loose bolts and crack damages on a lab-scale steel structure as well as on real bridge/building structures. It has been found that the proposed wireless impedance sensor nodes can be effectively used for local health monitoring of structural components and for constructing a low-cost and low-power but multifunctional SHM system as “place and forget” sensors.

7647-81, Session 10a

* Flexure-based mobile sensor design with application in structural damage identification

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Wireless sensing techniques have been widely explored for structural health monitoring in recent years, due to the advantages in reducing installation cost and time. Limitations of current wireless sensors have been identified in terms of power supply, communication bandwidth, communication range, computing power, etc. To address these limitations, mobile sensor networks may be adopted as a transformative change to wireless sensor networks. A mobile sensor network contains sophisticated mobile nodes with capabilities of sensing, wireless communication, and embedded computing. The sensor nodes may be passive for collecting structural response data, and/or active for applying excitation to a local area of the structure. Compared to conventional sensors with static configuration, mobile sensor networks can offer measurements with flexible deployment and high spatial resolution.

In this paper, we propose the design concept of a flexure-based mobile sensor. The flexure-based mobile sensing node is capable of maneuvering on ferromagnetic structures using motorized magnetic wheels. A compliant spring steel beam is mounted on the mobile sensing node for attaching/detaching an accelerometer onto/from the measurement location. Meanwhile, infrared sensors and Hall effect sensors are equipped to ensure the safety and reliability of the mobile sensing node. To validate the performance of the mobile sensing system, laboratory experiments are conducted with a steel portal frame. In the experiments, two flexure-based mobile sensing nodes are adopted to collect acceleration data for the damaged and undamaged structure under modal hammer excitation. Transmissibility function analysis is employed to identify the damage by comparing data from the undamaged and damaged structure.

7647-82, Session 10a

* Agent-based computational topology formation for automated modal analysis in dense wireless sensing networks

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Because of their low installation costs and autonomous data processing capabilities, wireless sensing networks have recently made it possible to intelligently instrument large civil structures with dense arrays of sensors. The data collected by these sensing networks can then be used to monitor the behavior and health of these structures over time. Perhaps the most important characteristics that can be measured by a network of wireless sensors are the dynamic (or modal) properties of a structural system. Modal frequencies and mode shapes, as well as modal damping ratios, can all be used to validate analytical models, improve design concepts, and detect and locate damage within a structural system. As such, it has become important to develop autonomous, in-network methods of determining the modal properties of a structure. In this study, an agent-based method is developed in which a network of wireless sensors autonomously organize themselves in order to compute modal properties through the use of the Frequency Domain Decomposition (FDD) method. The methodology developed herein uses market-based principles to create an optimal computing environment with respect to constraints on computational speed, FDD accuracy, communication bandwidth, and network power consumption. The proposed approach is validated through a series of modal tests performed using a network of wireless sensing prototypes.

7647-83, Session 10b

Pressure adaptive honeycomb: a new adaptive structure for aerospace applications

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A novel adaptive aerostructure is presented that relies on certified aerospace materials and can therefore be applied in conventional passenger aircraft. This structure consists of a honeycomb material which’ cells extend over a significant length perpendicular to the plane of the cells. Each of the cells contains an inelastic pouch (or bladder) that forms a circular tube when the cell forms a perfect hexagon. By changing the cell differential pressure (CDP) the stiffness of the honeycomb can be altered. Using an external force or the elastic force within the honeycomb material, the honeycomb can be deformed such that the cells deviate from their perfect-hexagonal shape. It can be shown that by increasing the CDP, the structure eventually returns to a perfect hexagon. By doing so, a fully embedded pneumatic actuator is created that can perform work and substitute conventional low-bandwidth flight control actuators.

A comparison of pressure adaptive honeycomb to other active materials shows that it belongs to the group showing the highest strains (in excess of 50%). For a pressure adaptive honeycomb that relies on compressed bleed air from the jet engine, a mass-specific energy density of 12.4J/g was calculated (on the par with SMA).

Pressure adaptive honeycomb was embedded into a 35%c adaptive flap on a NACA2412 wing section with a chord of 1.08m. Wind tunnel tests at a Reynolds number of one million demonstrated a shift in the cl-alpha curve upwards by an average of 0.3, thereby increasing the maximum lift coefficient from 1.27 to 1.52. This successfully demonstrated the application of pressure adaptive honeycomb embedded in a morphing aircraft structure.

7647-84, Session 10b

Detailed studies on the formation of piezoelectric β-phase of PVDF at different hot-stretching conditions

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Poly (Vinylidene Fluoride) or PVDF is promising material for transducer applications. PVDF exists in four crystalline phases viz., alpha, β,

gamma, and delta. The apolar alpha-phase is most stable and polar β-phase exhibits piezoelectric properties. In the present work, alpha-phase PVDF films have been converted to β-phase by hot stretching using a specially designed setup. The effect of stretching

temperature and stretching ratio on the evolution of β-phase has been studied from x-ray diffraction patterns, Line profile analysis of (110) reflection from β-phase indicates that grain size increases from 6 to 17 nm and micro strain decreases from 0.026 to 0.014 as stretching temperature increases from 50-80 degree C. Films prepared at different conditions have also been characterized for mechanical, thermal and surface features. In addition, Raman and infrared spectroscopy (IR) has also been used at various stages.

It is found that β-phase is achieved at all temperatures and stretching ratios. The conditions to achieve the beta phase have been optimized by checking the 2θ value corresponding to (110) reflection. Hot-stretching at 80°C with a stretching factor of 4 gave 20.8degree for 2θ of (110) reflection of β-phase. This value agrees well with the standard value quoted in the literature. For further studies, these stretching conditions are used to prepare the β-phase. These films give a value in the range 13-15 pC/N for d33.

To evaluate the performance of the sensor made out of this film, the vibration modes of cantilever have been simultaneously recorded with PVDF and PZT sensors. A comparison of the two sets of signals indicates the excellent performance of PVDF sensors.

7647-85, Session 10b

Thermodynamic modeling of martensitic phase transformations

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The unusual properties of shape memory alloys (SMAs) are due to solid-to-solid martensitic phase transformations (MPTs) which result from an instability of the material's crystalline structure. Accurate models of MPTs based on the material's atomic composition and crystal structure are currently not available. However, models of this type are required to computationally discover new SMAs.

This work aims to develop a lattice-dynamics model using a "first-order self-consistent approach" capable of capturing MPT behavior. In particular, atomic interactions are modeled using empirical potentials (the Morse pair potential is used as an example). In general, these potentials are determined from first-principles calculations such as electronic density functional theory simulations. The effects of atomic vibrations on the material properties are captured by computing the renormalized frequencies of atomic vibration using a set of self-consistent equations. A key feature of this approach is that the renormalized frequencies depend on both configuration and temperature. The model is, thus, able to capture "entropiclly stabilized" transformations such as those found in SMAs.

The model is demonstrated for a one dimensional bi-atomic chain. Morse potentials are chosen to illustrate the desired behavior and the capabilities of the self-consistent approach. The resulting model is evaluated by generating a stress-free bifurcation diagram consisting of the material's equilibrium states as a function of temperature. The bifurcation diagram reveals the existence of a hysteretic temperature-induced MPT. The ability of the model to predict temperature-induced MPTs indicates that it has the potential for use as a computational tool to discover new SMAs.

7647-86, Session 10b

Characterization of strain recovery behavior of shape memory polymer by nanoscratching test

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The nanoscaled operation of polymers is particularly challenging due to their significant compliance and low hardness, viscoelastic or viscoplastic response, and apt to destroy probe tip. The objective of this work is to examine the micro-nanoscale deformation and thermal induce recovery behavior of shape memory polymer. The copolymer shape memory material is synthesized by our Smart Materials and Structures Laboratory with certain percentages of epoxy and condensate. Instrumented nanoscratching is used to examine ambient temperature deformation of the epoxy SMP below their glass transition temperature. Temperature induced shape recovery of the scratching is studies using atomic force microscopy. The scratched surface is toweled at above Tg of the material and cooled down to ambient temperature. Then a scan of the surface profile is performed as a function of the increasing temperature from room temperature to a temperature above Tg until the scratch is fully recovered. Full recovery of mar has been recorded. The difference in height during temperature induced recovery is also recorded. Dynamic mechanical analysis is used to acquire the recovery behavior of the polymer with the function of recovery temperature and recovery time, which are critical for the development of the SMP-based applications. Furthermore, the difference between temperature induced shape recovery of the indentation and scratch is studied. The study will also provide insight on application of SMP in nanoscale through the investigation of the elastic, plastic and recovery deformation response of the SMP.

7647-87, Session 10b

Novel fabrication technology for three-dimensional high surface area pyrolized structures

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High specific surface area structures are used in a variety of applications including the production of highly sensitive biosensors, fabrication of separation membranes, in high throughput catalytic processing, and for the efficient electrodes in batteries and fuel cells. In many electrochemical applications (i.e. sensors, batteries) it's also critical to have good conductive properties of the fabricated high surface area structures.

Careful design of surface-to-volume ratio of the electrode surface is important for electrochemical energy generation such as in batteries and fuel cells. Although high surface area of electrodes facilitates better electrochemical reaction rate, it also increases the overall internal resistance of the cell. Thus more intelligent design of electrode geometries is required that maximizes current exchange while minimizing the resistance path for the current. One such geometry is ubiquitously existent in nature in the form of fractal structures.

We have invented a novel fabrication technology for creating high surface area, three-dimensional conductive structures based on the deposition and subsequent processing of the electroactive polymers (EAP). Further methods have been considered to exploit the fabrication technique in achieving fractal scaling of the electrode structures. The proposed fabrication technique is capable of fast and inexpensive production of high surface area structures with the designed geometry, porosity, and conductivity.

7647-88, Session 11a

Pavement roughness monitoring method using fiber optic vibration sensors

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Main purpose of pavement of the highway is to provide the safe and efficient surface of the road to the vehicles. In order to achieve the safe and efficient surface of the road, overall investigations after construction and every year inspection are performed. For maintenance of the pavement, inspections with 7.6 profilermeter or ARAN(Automatic Road Analyzer) are used, but they are not suitable for local in situ monitoring of the roughness of pavement while they are widely used for long range roughness of pavement.

Fiber optic sensor system, which is not corrosible semi-permanent, no influence by electromagnetic waves, and able to multiplex, can be expect to take an important part to assess the safety and residual estimate the life span of the highway pavement structure.

In this research, as in situ monitoring of roughness of pavement, we propose the vibration monitoring method using fiber optic sensors. We designed and produced prototype fiber optic vibration sensor packages. Laboratory impact tests with the sensors were performed. The sensors showed very good responsibility to the impact and nice damping shape like other ordinary accelerometers. Actual road tests with the prototype vibration sensor were also performed. The ambient vibration by the vehicles was used for the experiment.

7647-89, Session 11a

Development and laboratory validation of a low-cost time-of-fly fiber optic sensor

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This paper presents a novel elongation sensor based on direct measurement of the Time of Flight of short laser pulses in an optical fiber circuit. The technology was developed with the idea of producing very low cost fiber optic measurement systems with a single-channel Interrogation Unit (IU), and we employ ordinary and inexpensive electrical components: a nanosecond laser pulser, a photo-diode and a Pulse Width Modulation electronic circuit. For the same reason, the optical circuit consists only of bare fiber. In more detail, the optical path is divided into two lines, permitting intrinsic thermal compensation: one measuring fiber is attached to the structure, while the other is kept loose for reference. The system was developed in a number of prototypes and tested in the laboratory to validate its performance. The model of IU tested generates 1ns pulses at a frequency of 30kHz. Two optical arrangements were investigated: the first is a 100m long optical fiber coil, designed for a measurement base of about half a meter, the second is a 15 meter gauge-length sensor. Test results show that response of the system is almost linear and precision is of the order of 20-60 . A model of this sensor was embedded in a laboratory prototype of smart reinforced concrete beam, while other models have been installed in-situ in a historic building as part of the instrumentation of a pilot wireless monitoring system.

7647-90, Session 11a

Measures for identifying cracks within reinforced concrete beams using BOTDR

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BOTDR is one of the strain measurement technologies that is suitable for smart monitoring of civil engineering infrastructures, such as bridges. While the technology has the advantage of supplying spatially distributed data, it is currently limited to a spatial resolution of about 1m. This infers that the technology may lack the ability to identify the exact type and source of damage; that is, different geometrical configurations of cracking within a concrete beam may lead to similar BOTDR readings, and hence the exact nature of cracking might not be resolved by the BOTDR.

This study suggests different cracking indicators, and examines, both analytically and experimentally, their correlation with BOTDR readings of damaged reinforced concrete beams. The analytical part entails statistical analysis of thousands of cracking cases in fractured reinforced concrete beams and their effect on the simulated BOTDR readings. The analysis is conducted within COMSOL-Multiphysics, and is aimed to understand the correlation between the different cracking indicators and the beam curvature as would be obtained by the BOTDR. The experimental part consists of a controlled load test of a reinforced beam instrumented by BOTDR fibers, and is aimed to validate the analytical findings.

7647-91, Session 11a

Monitoring of stress distribution along a ground anchor using BOTDA

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The determination and monitoring of the stress distribution along a loaded ground anchor rod is essential for the understanding of the bearing behavior of this geotechnical structure. Thus, lots of interest has been put into measuring strain at distinctive points along anchor rods by various means of sensors, such as conventional strain gauges and, more recently, fiber Bragg gratings. Other approaches are based on elongation measurements in a very limited amount of rod sections. This can be basically seen as long-gauge strain sensors. Monitoring anchor rods, which offer strain readings in up to 4 sections are commercially available and are regularly used in constructions.

In this paper, a novel monitoring ground anchor using embedded optical fibers for the continuous strain assessment along the anchor rod is proposed and results from laboratory and field testing of such anchor rods are presented. Continuous strain along the embedded fiber cable is measured by Brillouin Optical Time Domain Analysis (BOTDA) through a commercially available measurement unit.

In a first step, different techniques of optical fiber integration into rods of 1.2m to 3.3m length have been carried out. Thereafter, the rods where strained stepwise in a tensile testing apparatus and optical strain measurements were taken at each load step. The optical strain was compared with independently acquired strain data. The evaluation of the laboratory testing led to the design and development of an 8m long monitoring ground anchor for field application. In 2009, this anchor has been integrated into a wall supporting an excavation pit and subsequently, anchor pull testing was performed. The optical strain data led to the successful monitoring of the stress profile in the 5.75m grouted section of this anchor. Additionally, the data could be used for the calculation of the applied pull out load in the free length of the anchor and the anchor head displacement. These results contribute towards the proof of serviceability for distributed fiber optic sensors in these kinds of practical approaches.

7647-92, Session 11a

Study on the reliability of distributed optical fiber sensors under fatigue load

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It is significant to improve the fatigue reliability of strain measurement for damage identification of important civil infrastructures under long-term fatigue loads, such as bridges and prestressed steel structures. In this paper, based on the distributed optical fiber strain sensing technique of pulse-prepump Brillouin Optical Time Domain Analysis(PPP-BOTDA), three types of optical fibers, i.e. single-mode optical fiber with Jacket (Type-A), UV resin-coated optical fiber (Type-B) and optical fiber with improved strain sensitivity (Type-C), were selected to study the monitoring reliability in low cycle fatigue experiment with different initial strain amplitudes. Three kinds of optical fibers were tested in unidirectional tension at certain cycle numbers. Preliminary experimental results show that the strains of the Type-A and Type-B drift much with cycle numbers, while the Type-C show little deviation from the true value. It is indicated that the monitoring data of Type-A and Type-B was not reliable under fatigue loading because of the fatigue damage accumulation of the optical fiber, while Type C had little effect on its reliability. As a result, optical fibers with improved strain sensitivity can be used in the long-term monitoring of large-scale structures under long-term fatigue loads such as bridges and prestressed steel structures.

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7647-93, Session 11a

Development of an optical fiber sensor to monitoring the formation of cracks in concrete structures

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Many times when a fissure in a concrete structure is discovered it is too late because the fissure has already propagated. Because of this, a fiber optic sensor for detecting fissures at their origin was sought to be developed. The goal of developing such a sensor was to monitor the formation of fissures in their initial stages before they propagate and by this way avoid the failure of a structure. The functionality of such sensor was demonstrated and was able to detect fissures early (from their origin) in any part of the structure. This sensor is innovative due to the fact that it can monitor the condition of a structure in a distributed way and not at points.

Interest in the supervision of structures in civil engineering has been growing constantly in order to improve the durability and safety of structures. Because of this, development of fiber optic sensors has been researched for a number of engineering applications. One of these applications is the continuous supervision of concrete structures.

This type of continuous supervision has many advantages when compared to visual inspection. This is because visual inspections sometimes cannot detect fissures inside a structure unless these fissures propagate to the surface, which many times cause irreparable damage. The continuous supervision of optical sensors allows the permanent monitoring of the condition of a structure. These sensors are recommended for structures that have variable loads such as bridges and dams. The ability to permanently monitor a structure has been recognized as an important development in the supervision of civil infrastructure.

7647-94, Session 11a

Development of a wireless node for fiber-optic sensing

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Structural health monitoring (SHM) is a developing field of research with a variety of applications including civil structures, industrial equipment, and machine process monitoring. The first and most important stage of any SHM system is the design of the sensing architecture, which is traditionally composed of transducers that measure some physical response at discrete points. Distributed fiber-optic sensing methods have a significant advantage over traditional discrete sensing systems, in that they can be used to obtain continuous measurements along the length of an optical fiber to provide real-time monitoring data. However, fiber-optic sensing equipment is often heavy, bulky and difficult to install in situ. Furthermore, physical access to the structure being monitored may be limited, as is the case for rotating blades or unmanned aerial vehicles, motivating the need for wireless transmission of sensor readings. This paper presents a first step in the development of a compact wireless node for fiber-optic sensing, with which light intensity measurements are used to obtain a first-order strain approximation. Experimental results from a wind turbine blade are compared with those obtained using conventional fiber-optic sensing equipment.

7647-95, Session 11b

Modeling and simulation of heterogeneous electronic system based on smart sensors for aerospace structures health monitoring

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It is well-know that continuous revisions of aerospace structures are necessary to detect damage on aircraft. Therefore, developing a preventive maintenance in aircraft ensures higher security and cost reduction. In this work, a modeling and simulation environment of Heterogeneous Electronic System is described. This system helps to identify high risk damage areas which have been produced by environmental conditions. This smart solution include: a three axis accelerometer, capacitive humidity sensor, low voltage temperature sensor, pressure sensor, and stress-strain. Signal acquisition techniques based on voltage to frequency converters, capacitance to frequency converters and frequency to code conversion has been also used.

The behavioral modeling is performed on the environment MATLAB®/SIMULINK® with target of translate it into a structural VHDL-AMS code able to be co-simulated with VHDL descriptions for digital signal processing circuitry. The model has a user interface for easy interaction that permits inputs parameters, which are sensing, access to visual indicators, graphics of response time and frequency.

A mathematical model for each sensor is implemented within simulink block diagrams. When the sensors are modeled, besides the conversion, there are multiples factors that influence in their performance each as: noise density, temperature, supply voltage, frequency that are simulation in real time allowing the output signals more precise and reliable. The values of the supply voltage, and current, and scale factor for the sensors are intended for this application over the specific range.

An excellent way to acquire a complete range of signals presenting low nonlinearly effects and high accuracy are frequency acquisition techniques. The output signal of each sensor is different, so that the system performs analogue signals conversion to the frequency dominium. Concretely four signals to frequency converters are employed in this work: the CMOS differential oscillator (relaxation model of one channel), relaxation model of two channel, resistance to voltage converters, and voltage controlled oscillator (VCO). Good noise immunity, high output voltage range, a widest dynamic range, and an acquisition circuitry reduction are some advantage of this frequency data acquisition method. Furthermore the system performs frequency to code conversion based on indirect count method (ICM), and the dependent count method (DCM).

One important aspect of the design methodology is the co-simulation of circuitry. For analogue signals to frequency converters have been performed a mathematical model of which output frequency varies as a result of changing the transduction value, providing symmetrical and wide range frequency outputs. Therefore is necessary to force the output oscillation signal to +VDD converting it in to square signal employing a pulses generator. Power supply rejection ratio (PSRR), phase noise (PNoise), output spectrum (PSS), and current consumption (RMS) are parameters to be considered in order to estimate the environment of oscillator.

7647-96, Session 11b

On the combination of asymptotic and direct approaches to the modeling of plates with piezoelectric actuators and sensors

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The paper presents a novel complex approach towards mathematical modeling of the performance of thin structures integrated with strain-type sensors. Namely, we analyze the response of a plate with piezoelectric patches under mechanical and electrical loads.

We consider a two-dimensional material surface with particles having five mechanical degrees of freedom (translations and rotations) and one electrical (potential difference between the surfaces). The variational principle of the direct approach provides both the system of equations and the expressions of the local strain measures, on which the total enthalpy in the cross-section depends.

As the expression of enthalpy cannot be derived in the framework of the direct approach, the asymptotic analysis of the three-dimensional problem is an essential part of the research. We consider the complete system of equations for a piezoelectric plate with the material properties, varying over the thickness. Condition of compatibility of strains plays a central role in the analysis. Looking for the solutions varying slowly in the plane of the plate, we find the terms, which dominate as the thickness tends to zero. The relation to the direct approach is established with the help of the expression of the virtual work of internal forces. The integrated total enthalpy of the three-dimensional model complements the two-dimensional formulation.

A finite element scheme was implemented based on the suggested model, and successful comparison with full-scale three-dimensional solutions was performed. The results serve as a basis for the analysis of geometrically nonlinear shell structures as well as for model-based health monitoring and optimal sensor placement.

7647-97, Session 11b

* Acoustic emission detection and energy transduction with piezoelectric wafer active sensors

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Structural health monitoring (SHM) is important for reducing maintenance costs while increasing safety and reliability. Acoustic emission (AE) occurs due to stress waves generated when there is a rapid release of energy in a material, or on its surface. Piezoelectric wafer active sensors (PWAS) used in SHM applications are able to detect structural damage in both active and passive mode. PWAS are small, lightweight, unobtrusive, and inexpensive and achieve direct transduction between electric and elastic wave energies.

This paper starts with a literature review of the state of the art on the AE detection method and AE detection using PWAS. Numerical verification of AE event and wave propagation in steel and aluminum substrates was simulated by finite elements method. The energy transduction of PWAS and substrate was considered. The experimental result and numerical simulation shows the trends in energy flow behavior during AE events. This indicates that PWAS can be used as an AE sensor and with proper adaption; it can replace the bulk traditional AE sensors for SHM applications, e.g. steel bridge health monitoring.

7647-98, Session 11b

Shear lag solution for structurally attached active sensors

G. Santoni-Bottai, V. Giurgiutiu, Univ. of South Carolina (United States)

In nondestructive evaluation (NDE) applications, induced strain actuators are embedded in structure elements to control the structural deformation. Piezoelectric wafer active sensors (PWAS) have been used as actuators in application with beams, plate, and truss elements. Under electric excitation, the PWAS undergoes oscillatory contractions and expansions which are transferred to the structure through the bonding layer and thus excite Lamb waves into the structure. The transducer is bonded to the plate with an adhesive layer. The contractions and expansion of the PWAS is transmitted to the material through the bond layer. Due to the reciprocity of the piezoelectric properties, the PWAS can be also used to detect Lamb waves and transform them to electric signals.

Crawley and deLuis developed an analytical model of the mechanical coupling of segmented piezoelectric actuators to the dynamic of the structural member. The configuration they studied was of two piezoelectric elements bonded by a finite bonding layer to an elastic structure. The solution proposed was the classic shear lag solution. They showed that when the shear lag goes to zero, the solution reduces to the simpler model of the perfectly bonded piezoelectric. They assumed that the strain distribution in the piezoelectric actuator was a linear distribution across the thickness, further more they assumed that the strain distribution across the structure could be a linear Bernoulli-Euler type or a uniform extensional strain.

Although the solution of Crawley and Luis is only valid at low values of the frequency-thickness product (i.e., where the axial and flexural wave approximation holds), this solution has been subsequently used by other authors for describing the shear-lag transfer at ultrasonic frequencies where the axial and flexural approximation to the S0 and A0 modes no longer holds and where more than these two fundamental modes may be present.

The present paper will present the extension of the work of Crawley and deLuis for the case of two modes at high frequency and it will introduce the problem of deriving the interfacial shear stress between PWAS and structure for two or more wave modes present.

7647-99, Session 11b

Conductor width independence case of the self-resonance quality factor of semiadditive planar coils on a magnetoelastic substrate

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A magnetostrictive bending sensor with rectangular planar coil is investigated. Its purpose is to measure contactlessly mechanical quantities of non-vibrating structures using an alternating magnetic field. The coil turns are electrodeposited by pattern plating on top of a magnetostrictive Galfenol layer and a thin magnetron sputtered SiO2 insolation layer.

The achievable conductor height depends on the photoresist and conductor width and gap using standard semiadditive technology. Therefore a large conductor height, e.g. 20..100 µm, reduces the number of turns and the coil resistance but is more time consuming during manufacturing. For this reason the coils investigated in this paper were manufactured with a constant height h = 10 µm and gap and variable width.

The sensor is operated near its electrical self-resonance between 5 and 40 MHz and requires a high quality factor. It determines the number of periods in the impulse response and the bandwidth of the resonance circuit. FEM-simulations show that the quality factor is almost independent on the conductor width under the design restrictions when skin and proximity effects are included.

It could be confirmed by measurements obtained from sensors with three different turn numbers and conductor widths depending on the turn number that the self-resonance quality factor is almost constant when a semiadditive technology is used to manufacture the coil turns. This is a contradiction to the low frequency properties of the quality factor. The reason is mainly the displacement of the electrical current by the proximity effect. An effective conductor width could be determined.

7647-100, Session 11b

Electromechanical network modeling applied to magnetoelastic sensor design

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Electromechanical network models are used in this paper to analyze a prototype micro-gyro sensor that employs the magnetostrictive alloy GalFeNOL for transduction of Coriolis induced forces into an electrical output at a given rotational velocity. The concept takes advantage of the principles employed in vibratory gyro sensors and the ductile

attributes of GalFeNOL to target high sensitivity and shock tolerance. The sensor is designed as a tuning fork structure which reacts with vibration of the prongs in tangential direction due to an excited vibration in redial direction. A GalFeNOL patch attached to the ax.-rad.-surface changes its permeability depending on the bending. When it is surrounded by a solenoid coil and a constant electrical current creates a magnetic field then this field fluctuates with the prong vibration. The induced voltage is used as sensor output and the sensor sensitivity calculated. A rotational velocity being effective on the tuning fork structure causes an amplitude modulation of the excitation frequency which is the carrier frequency.

The prongs are modeled as dynamic bending beams which are surrounded by a solenoid coil. A circuit representation of the electromechanical system is derived, which enables an understanding and explanation of the behavior of thiss system involving different physical domains, as well as fast analytical and numerical calculations, e.g. with pSpice.

In first experiments the magnetic field at the end of the sensing prong was measured using a the GMR-sensor. In the frequency spectrum predicted sidebands of the adjusted 20 Hz rotation can clearly be recognized.

7647-191, Session 11b

Optical fiber chemical sensors with sol-gel derived nanomaterials for monitoring high temperature/high pressure reactions in clean energy technologies

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Optical spectroscopy is an ideal technique to indentify the existence, and measure the concentration of chemical compounds in samples due to the existence of figure-print absorption spectrum of chemical compounds. In order to interrogate a sample, techniques must be developed to send a probing light beam into the sample, collect light transmitted or reflected from the sample, and detect the intensity of light being transmitted or reflected at specific wavelength. Presently, the application of optical spectroscopic techniques for interrogating heterogeneous samples is still a tough challenge. This is especially true for the high temperature/high pressure (HTP), corrosive reaction systems in clean energy industrial processes, such as coal or bio-oil gasification, syngas reforming and cleaning. The samples in such reaction systems contain corrosive gaseous molecules, liquid droplets and solid particles, which not only cause optical interference, but also damage the optical windows which are in contact with the sample.

Total internal reflection spectroscopy (TIRS) is one of the advanced optical spectroscopic techniques could be used for analyzing such heterogeneous reaction system.1 In TIRS, the interrogating light is guided inside a waveguide. The interaction of the evanescent wave (EW) of light guided inside the waveguide with species on the surface of the waveguide is monitored. Therefore, the TIRS technologies avoid the interferences of a continuous changing scattering signal when used to analyzing heterogeneous samples. Present state-of-the-art TIRS uses prisms or planner waveguides for bringing light to interact with samples. These optical elements are not corrosion resistant, and their optical properties deteriorate with time when deployed into a corrosive HTP reaction system. In addition, the sensitivity of EW absorption techniques is not as high as traditional optical absorption spectroscopy, and it is difficult to detect the intrinsic optical absorption signal of most compounds with traditional TIRS.

In an optical fiber light is guided via total internal reflections, and therefore, optical fibers are appropriate to perform TIRS. The silica optical fibers are robust, corrosive resistant, and can work at temperatures up to 1000 oC. In addition, a chemical reagent can be coated on the surface of a silica fiber in order to introduce chemical reactions, which convert optically insensitive species to optically sensitive compounds for detection with fiber optic TIRS. These features make optical fiber TIRS very attractive for observing HTP reactions in clean energy processes. The author's group has been developing optical fiber chemical sensor (OFCS) technologies for monitoring trace gases species in high temperature gases using nanomaterials coated silica optical fibers as transducers. This paper describes the OFCS developed in the author's laboratory for monitoring trace NH3, H2S, H2, CH4 in high temperature gas samples.2,3 In addition, the challenges in developing OFCS for monitoring HTP reactions related to clean energy processes will also be discussed.

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7647-101, Session 12a

Modeling and analysis of hybrid energy storage systems for wireless sensor networks

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Ambient energy harvesting has been employed to extend the lifetime of wireless sensor networks. However, the network lifetime is still limited by the cycle life of rechargeable batteries. Alternatively, supercapacitors have extremely long cycle life - on the order of millions of cycles. A hybrid energy storage system (HESS) that leverages the complementary strengths of rechargeable batteries and supercapacitors can significantly increase the lifetime of wireless sensors. To provide design guidelines for the hybrid storage system, the HESS model is developed and the storage system performance is evaluated under different situations. The HESS model consists of five components: energy source, energy consumer, supercapacitors, rechargeable batteries and switch control module. The performance of HESS is evaluated in terms of two metrics: wireless sensor lifetime and energy conversion efficiency. Different HESS configurations are investigated with varied energy source and energy consumer profiles. The results indicate that the HESS performance strongly depends on the characteristics of energy source (power and duration of an energy pulse, timing sequence and energy ratio between different pulses) and energy consumer (whether it is time critical and its relative magnitude compared with the energy source). A tradeoff is usually observed between the two performance metrics. However, under certain circumstances a specific HESS configuration can outperform the rechargeable battery only storage system in terms of both metrics. The results also suggest that an adaptive HESS that dynamically configures the storage devices based on the energy source and consumer profiles may have better performance comparing with a fixed HESS configuration.

7647-102, Session 12a

Power harvesting from microbial fuel cell

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Microbial Fuel cells (MFCs) are batteries driven by bacteria. MFCs have the potential of powering small sensors in remote areas and disposing of organic waste safely as they harvest the energy stored in the waste products. From previous research in this field, a few important factors for MFC performance have been identified. These include the internal resistance of MFC, the surface area of anode with catalyst for the biofilm development, the type and number of bacteria, and the abundance of nutritional supplies to the bacteria. With internal resistance as the focus of this MFC research, this experiment uses previous discoveries to develop and optimize the single chambered fuel cell for large-scale applications.

A variety of methods were applied to improve MFC efficiency. Mainly, the researchers employed design techniques to increase the surface area of the electrodes, so that more of the generated electrons could be transported to the anode. In addition to that, several other measures

were implemented to reduce the internal resistance, namely, adding ionic content, as well as introducing conductive particles such as carbon powder. These resulted in findings crucial to MFC technology.

7647-103, Session 12a

A combination of energy harvesting methods to power wireless sensor networks efficiently

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Since there is a growing demand in wireless monitoring techniques, an efficient, long-term, power source for sensor nodes becomes more and more necessary. This is especially true for nodes recording highly dynamic data like acoustic emissions or vibrations.

A sensor network system is presented measuring pseudo-static (e.g., temperature, humidity or strain) and in concert with dynamic data from acoustic emissions and vibrations. A pre-processing of the data from the different sensors is done in the node. Moreover, clusters of sensor nodes are formed within a sub-network to compare the pre-processed data. All these efforts are made to limit the data transfer effort through the network and to the sink. Since a long sensor node life is required conventional power solutions need to be supported by novel techniques. In particular, this paper deals with the implementation of hybrid energy sources to sensor nodes. A mix of batteries and super capacitors are augmented by techniques consisting of solar cells or modules harvesting energy using the Seebeck effect.

The paper describes the efficiency of the different harvesting methods as a function of various environmental conditions. The amount of energy harvested using the Seebeck effect is closely related to the mounting-surface materials (e.g. steel, stone or concrete), the materials' albedo, and air flow conditions.

7647-104, Session 12b

A new architecture for the implementation of tunable mechanical monolithic horizontal sensors

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This paper describes a new mechanical version of the monolithic tunable folded pendulum, developed at the University of Salerno, configurable both as seismometer and, in a force-feedback configuration, as accelerometer. Typical application of the sensors are in the field of geophysics, including the study of seismic and newtonian noise for characterization of suitable sites for underground interferometer for gravitational waves detection. The sensor, shaped with precision machining and electric-discharge-machining, like the previous version, is a very compact instrument, very sensitive in the low-frequency seismic noise band, with a very good immunity to environmental noises. Important characteristics are the tunability of the resonance frequency and the integrated laser optical readout, consisting of an optical lever and an interferometer. The theoretical sensitivity curves, largely improved due to a new design of the pendulum arms and of the electronics, are in a very good agreement with the measurements. The very large measurement band (10-6 Hz - 10 Hz) is coupled to a very good sensitivity (10^-12 m/sqrt(Hz) in the band 0.1 - 10 Hz), as seismometer. Prototypes of monolithic seismometers are already operational in selected sites around the world both to acquire seismic data for scientific analysis of seismic noise and to collect all the useful information to understand their performances in the very low frequency band (10^-6 - 10^-3 Hz). The results of the monolithic sensor as accelerometer (force feed-back configuration) are also presented and discussed. Particular relevance has the sensitivity that is better than 10^-11m/s^2/sqrt(Hz) in the band 0.1 - 10 Hz. Finally, hypotheses are made on further developments and improvements of monolithic sensors.

7647-105, Session 12b

Mechanism governing surface stress development associated with hybridization of monomolecular DNA film and formation of alkanethiol SAM on gold surfaces

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Surface stress changes associated with hybridization of surface immobilized DNA molecules and formation of alkanethiol SAM are measured and a multiscale model is developed to identify the mechanisms underlying the measured response. A novel interferometry technique employing two adjacent micromachined cantilevers a sensing/reference pair is used to measure the surface stress development. Experimental results indicate that surface stress develops only on exposure to complimentary strands (specific binding) and is not affected by exposure to other single strand DNA (non-specific binding).The surface stress change as a function of analyte concentration is used to determine the disassociation constant associated with hybridization reaction. Calculated value of the disassociation constant agrees well with independent measurements performed using isothermal titration calorimetry (ITC). Measured surface stress changes and disassociation constants are used in a multiscale analysis of monomolecular film in order to estimate the interaction potentials between hybridized DNA. Experiments on alkanethiol SAM formation show that the adsorption of the self-assembled monolayers (SAMs) on a gold surface induces surface stress change that cause a deflection or deformation of underlying substrate. Molecular dynamic (MD) simulations are applied to study the mechanism behind the phenomenon. Two different potential applications, embedded atom method (EAM) and surface embedded atom method (SEAM), are used in the MD simulations separately. Quantum chemical calculations are used to modify the potentials for gold atoms to model the reported surface reconstructions. The simulation results show that the surface energy due to gold-sulfur interaction is the dominant part of the phenomenon.

7647-158, Session 12b

Development of nano-based sensors for the detection of improvised explosive devices

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Tragic world events have called for a need for fast, reliable, and more deployable methods of detection of improvised explosive devices (IED) than trained canines and visible detection by x-ray screening technologies. Anodized Aluminum Oxides (AAO) are ideal substrates for chemical sensor developments. The nano-porous structure provides small pore-to-pore distance and large surface area. These unique qualities allow optical interference in the visible spectrum when the film thickness is in the proper range. By coating the nano-wells of the oxide surface first with a thin film of a noble metal followed by a monolayer of a target-specific chemical, detection of trace amounts of explosive materials becomes possible. Research has shown that the carboxyl group of 6-mercaptopyridine-3-carboxylic acid (6-MNA) has an attraction to the nitro groups of TNT while the thiol group of 6-MNA creates a self-assembled monolayer on the substrate. By utilizing these chemical properties together, UV-vis spectrometry can detect a shift in the visible spectrum on the coated AAO substrate as the 6-MNA structure attracts trace amounts of TNT particles. The sample characterization with use of AFM, Raman, the interference measurements, and IED detection will be presented.

Conf. 7647: Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems

7647-107, Session 12c

Damage detection based on nonlinear prediction model to large-span bridges

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A new method based on volterra nonlinear model is proposed in this paper to detection the damage in large-span bridges. Random decrement technique is used to acquire free attenuation signals from stochastic excitation responses and associative neural network is used to obtain normalization vehicle excitation response signals, thus, output-only information is need in this method and more information can be utilized when there is the same amount of sensors. The nonlinear prediction model is built using volteera model, which can capture accurately the nonlinear character in the response signal, the method to choose the delay time and embedding dimension is discussed. The volteera model is built up using signals obtained from the health bridge and the prediction error between the theoretical prediction time history values and the measurement signals is treated as damage detection index (DDI). The threshold of DDI is get from the statistical value when the bridge is health. If a new DDI, calculated from unknown condition of the bridge, exceed the threshold, damage may occur. Different damage cases are simulated to a five span continuous beam and a large-span bridge respectively. Results show that the nonlinear prediction model can not only detect whether there is a damage or not , but also can detect the damage location at some degree.

7647-108, Session 12c

Field vibration tests-based model update for system identification of Wondongcheon railway bridge

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During the last decade, the development of methodology for accurate and reliable condition assessment of civil structures has become increasingly important. In structural engineering analysis and design, the finite element (FE) analysis is a powerful and useful tool to simulate the behavior of real structure. Hence, an accurate FE model is prerequisite for civil engineering applications such as damage detection, health monitoring and structural control. However, it is not easy to generate the accurate FE model for the complex structures, because material properties and boundary conditions of those structures are not completely known. For this reason, it is usual to make simplifying assumptions when modeling the structure. As a result, the initial FE model may not truly represent all the physical aspects of an actual structure. On the other hand, it is generally agreed that experimental results can be considered as more reliable than numerical ones due to the advances made in instrumentation and measurement techniques. Therefore, it presents an important issue that how to update the FE model using experimental results so that the predicted modal properties match the measured ones.

In this study, a FE-model update technique for system identification of real railway bridges using field vibration test results is presented. The objective of the model update is to minimize the difference between the numerical and experimental modal parameters and to provide the baseline model of the target structure which can be used for further analyses. In order to achieve the objective, the following approaches are implemented. Firstly, Wondongcheon bridge which is a steel girder railway bridge located in Yangsan, Korea is selected as the target structure. Secondly, natural frequencies are numerically calculated using a three-dimensional FE model which is established for the target structure. Thirdly, in order to choose the proper parameters for adjustment, the eigenvalue sensitivity of potential updating parameters is analyzed from initial FE model. Fourthly, the FE model is updated by using eigensensitivity analysis of the corresponding natural frequencies which are experimentally measured from vibration test on the bridge. Finally, multiple structural subsystems are performed by step-by-step updating procedure. Based on updated results, the baseline model of the Wondongcheon railway bridge is identified.

7647-109, Session 12c

Application of nonlinear observer in hysteretic model updating

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The use of model updating have been widely applied in structural health monitoring, FE model validation and refinement, material identification from vibration testing, FE model reduction, and so on. So far, the essential assumption that updating model is based upon, is that the linear dynamic model of the investigating structure. However, with the need of the identification of structural systems exhibiting nonlinear hysteretic behavior, usual linear dynamic system assumption collapse and the commonly used modal analysis tools can no longer be applied.

In the recent years, several observer-based nonlinear hysteretic modeling techniques have been developed (Smyth). Considering the random nature of ambient loading condition, extended Kalman filter (EKF) has also been introduced into structural model identification (Yang). However, the deterministic observers usually demand a well-devised mathematical adaptive model a priori, and the optimization process sometimes involves results in a local solution. For the EKF, since the basic assumption is the linearization of the nonlinear model at each observing data point, for highly nonlinear models, it is difficult to obtain an accurate solution within a small time frame.

In this paper, an adaptive stochastic observer-based model updating scheme has been proposed to identify the key parameters of a certain type of structural hysteresis. This technique is applicable to both linear and nonlinear structures under random excitations. A steel frame model with nonlinear hysteretic joints is presented as a numerical example. With the simulation results for tracking the parameters of the nonlinear model, the accuracy and efficiency of the proposed method can be well demonstrated. The updated nonlinear structure model can be used not only for damage localization and quantification, more importantly, it could be used for predicting the future structural behavior.

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7647-110, Session 13a

Damage identification of large-Scale structures with incomplete measurements

H. Huang, Tongji Univ. (China); J. N. Yang, Univ. of California, Irvine (United States)

A challenging problem in structural damage detection based on vibration data is the requirement of a large number of sensors and the numerical difficulty in obtaining reasonably accurate results when the system is large. To address this issue, the substructure identification approach may be used. A large-scale structure can be divided into a number of small-scale substructures and the damage identification of the entire structure can be carried out progressively through the identification of each substructure. Due to practical limitations, the response data are not available at all degrees of freedom of the structure and the external excitations may not be measured (or available). In this paper, an adaptive damage tracking technique, referred to as the sequential nonlinear least-square estimation with unknown inputs and unknown outputs (SNLSE-UI-UO) and the substructure approach are used to identify damages in the structure. In our approach, only a limited number of response data are needed and the external excitations may not be measured, thus significantly

reducing the number of sensors required and the corresponding computational efforts. The accuracy of the proposed approach is illustrated using a 10DOF and a 50DOF linear structure. Substructure approaches with and without overlaps will be compared in terms of accuracy and number of sensors required. Simulation results demonstrate that the proposed approach is capable of tracking the local structural damages as well as identified the parameters of the entire structure, and it is suitable for both local and global structural health monitoring.

7647-111, Session 13a

Data processing strategies for health monitoring of a long span suspension bridge

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Various uncertainties involved in the experimental and identification processes that impact the reliability of St-Id, these serve as a barrier to more widespread applications in civil engineering practice. Recognizing the impact of various uncertainty mechanisms and taking appropriate measures to quantify, bound and mitigate their impacts will greatly benefit bridge owners and engineers. Data proposing of the vibration test data of a long-span suspension bridge is leveraged as an example to illustrate strategies for coping with the challenges presented above. First, data pre-processing strategies including data inspection, time window selection, band-pass filtering, averaging and windowing are proposed to reduce data errors and to detect possible causes of outliers in the measured data (higher traffic, higher wind, temperature shocks, construction activity, unusual activity, etc). Subsequently, three independent St-Id post-processing methods, including Peak-Picking, PolyMAX, and Complex Mode Indicator Function (CMIF), are applied for accurate structural modal parameter identification. Statistical analysis of the St-Id results from a number of time history windows are also performed, providing effective ways to investigate window relevance, data reliability and how they affect St-Id results. The identification results obtained for both the bridge spans and the towers demonstrate that the demonstrated field testing and data processing methods may provide a reliable bridge characterization.

7647-112, Session 13a

A new substructure method for condition assessment of highway bridges under moving vehicles

X. Zhu, B. Uy, Univ. of Western Sydney (Australia)

The research effort on the use of vibration data to detect and quantify structural damage in civil engineering constructions has been increasing during the last decade. Most of the currently available methods aim to relate the changes in natural frequencies, mode shapes or frequency response functions to the occurrence of structural damage. It is attracting significant research attention is to the use of structural response from operational dynamic loads in damage detection procedure

This study is to use a new substructure approach to identify the interaction force of the vehicle-bridge system from the bridge responses, and the local structural damage is identified from the change in the interaction forces. The vehicular loads are modelled as a group of moving loads moving at a prescribed velocity, and the bridge is simplified as a continuous Euler-Bernoulli beam simply-supported at both ends. The damage function is used to simulate the crack damage in the reinforced concrete beam. The effect of the parameters of the vehicle-bridge interaction system on damage detection is studied. Numerical simulations shows that the interaction force is sensitive to the local damage of the bridge and the proposed method is effective and accurate detect the location and extent of the structural damage of highway bridges in operational condition.

7647-113, Session 13a

Identification of modal macro-strain vector based on distributed dynamic macro-strain under ambient excitation

W. Hong, Southeast Univ. (China); Z. Wu, Ibaraki Univ. (Japan); C. Yang, G. Wu, S. Shen, Southeast Univ. (China)

Although the modal macro-strain vector (MMSV) is verified to be sensitive to structural damage in laboratory experiments, it is difficult to be accurately obtained because of the uncertainty of macro-strain frequency response function (FRF) under ambient excitation in practical monitoring. This paper proposes that the MMSV is determined with the assumption that white noise excitation can be seen as a proper substitute for ambient excitation. Impulse response function based on macro-strain is proposed and proved to be Fourier Transform Pair with macro-strain FRF. Then absolute value of MMSV can be uniquely determined by auto-power spectral density of dynamic macro-strain response under white noise excitation. Numerical simulation case suggests that absolute value of MMSV is in good agreement with the results obtained by modal analysis. It can be concluded that structural damage can be confirmed under ambient vibration in actual structures with accurate distributed macro-strain measurements.

7647-114, Session 13b

Haptic interfaces using dielectric electroactive polymers

M. Y. Ozsecen, C. Mavroidis, M. Sivak, Northeastern Univ. (United States)

Quality, amplitude and frequency of the interaction forces between a human and an actuator are essential traits for haptic applications. A variety of Electroactive Polymer (EAP) actuators can provide these characteristics simultaneously with quiet operation, low weight, high power density and fast response. In this paper, a rolled type Electro Active Polymer (RDEAP) actuator is used to demonstrate the above mentioned properties by means of a) heart beat simulation and b) Virtual Reality (VR) environment. In the heart beat simulation, the heart signals are acquired using a wireless heart rate sensor and is sent to NI LabVIEW through a network protocol. The RDEAP is then used to simulate the heart beat. From the preliminary tests, users have experienced a close resemblance between the haptic feeling of the simulated RDEAP and the natural beating of the heart. In the VR example, an open loop control via inverse model is implemented on RDEAP and a virtual pump with variable stiffness is generated to inflate a balloon on the computer monitor. Python and Panda3D software programs are used to develop the 3D environment to animate forces and manage their interactions in parallel with NI LabVIEW. Usability tests were conducted to evaluate the quality of actuation. By means of these two examples, it is demonstrated that a) haptic simulations can be like a heartbeat and they can be sent to a remote location b) through VR, some actuator properties like the stiffness of the EAP can be tuned for a variety of applications.

7647-115, Session 13b

Design of a quick response SMA actuated segmented nut for space release applications

X. Zhang, X. Yan, BeiHang Univ. (China); Q. Yang, China Academy of Space Technology (China)

Spacecrafts require a variety of separation and release devices to accommodate separation from the launch vehicle and deployment of heat radiation panels, solar arrays and other appendages. The traditional pyrotechnic release devices have the drawbacks of high shock and contamination. Some release devices using segmented

nut and SMA(with the form of wires or columns) were developed to overcome these drawbacks, but they faced the disadvantages of large size or complex structrues or unavailability of auto-reset

This paper proposes a design scheme of release device using segemented nut and SMA wire. In order to enlarge the SMA wire's acutation distance in a limited installation room, the SMA wire was bending through a gliding bearing. Also,a cylinder structure with small special slopes inside were designed to realize quick auto-reset, which made the release device convenient for ground tests. Since the release device responds quickly, it is very convenient to use when multi release devices are required. In order to validate the release device's function, ground deployment tests were carried out.

Tests results shows: under 6 v power supply, the quick response release device can finish release function within 0.3 second, and when two devices are used, they almost release at the same time. (the difference of release time between two devices is less than 0.04 second)Environment tests show that the device works well under 70 degree Celsius. It's concluded that the innovative space release device developed in this paper possesses the advantages of small size, quick response and auto-reset has a potential use in space engineering.

7647-116, Session 13b

Ultrasonic/sonic drill for high temperature application

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Venus is one of significant scientific targets for NASA and its environment represents several extremes including high temperature (460°C) and high pressure (~9 MPa). New rock sampling tools able to be operated in these conditions are required for surface in-situ sampling/analysis missions. Piezoelectric materials such as LiNbO3 crystals and Bismuth Titanate are potentially workable at temperature range on Venus. A study of the feasibility of producing piezoelectric drills that can operate in the temperature range up to 500°C was conducted. The study includes the high temperature properties investigations of engineering materials and piezoelectric ceramics with different formulas and doping. Several prototypes of Ultrasonic/ Sonic Drill/Corers (USDC) using the high temperate piezoelectric ceramics and single LiNbO3 crystal were fabricated. The transducers were tested by scanning the impedance at both small signal and large signal level. The drilling performances were tested at temperature up to 500°C. We will present the detailed results of our study and discuss the future work on performance improvements.

7647-117, Session 13b

Shape memory polymer actuator technology

F. Auffinger, Cornerstone Research Group, Inc. (United States)

Cornerstone Research Group Inc. (CRG) is developing low-cost, lightweight, shape memory polymer (SMP) actuators for use in the deployment of rigid aeroshells. The SMP actuator technology has been selected for use because of its ability to store energy and release that energy on demand with little requirement for power.

During the Phase I SBIR effort, CRG demonstrated the feasibility of using an SMP actuator for the deployment of a subscale, rigid, deployable aeroshell. The follow-on Phase II effort improved upon the Phase I actuator technology through the application of finite element analysis and testing. This work resulted in the manufacture of a full-scale actuator 0.127m long and 0.102m in diameter that was able to develop more than 40lb-ft of torque during actuation.

A conformal cartridge heater (CCH) was developed in parallel to solve the problem of transferring heat stimulus into the SMP materials. The CCH maintains surface contact with the walls of the SMP actuator throughout the actuator's range of motion to optimize the heat transfer between the heating surface and the SMP material surface.

The SMP actuator also has the potential of moving or deploying mechanisms simply through environmental stimulus. Since CRG is able to custom tailor the material properties of the SMP, broad application of this technology is possible.

7647-118, Session 13c

Experimental verification for the accuracy of a distributed sensitive fiber optic sensor under small strain variation and temperature variation

S. Shen, Southeast Univ. (China); Z. Wu, Ibaraki Univ. (Japan); C. Yang, S. Song, G. Wu, Southeast Univ. (China)

In actual structures, the daily change of strain may be smaller than 30~50με, which is approximately equivalent to the measurement errors of commercial instruments based on Brillouin scattering for distributed strain monitoring. Compared with two common fiber optic sensors (FOSs), the accuracy of a distributed sensitive fiber optic sensor (DSFOS) based on the pulse-prepump Brillouin Optical Time Domain Analysis (PPP-BOTDA) is tested under small variation about 10~15με. The results shows that the measurements of these common fiber optic sensors have large difference to the true values because of the uncontrolled measurement error about 30~50με. But the difference between the measurements from the DSFOS and the true values is much smaller evidently. The measurement error of the DSFOS is only about 10~12με. Furthermore, the accuracy of temperature measurement of the PPP-BOTDA is 1°C, which is corresponded to 20με. With the constant strain applied in these FOSs in simulated temperature cycles, there is fluctuation in the measurement data from contrast FOSs due to the temperature measurement error for compensation of strain measurements. The measurement data of the DSFOS can keep good stability which is suitable for daily structural distributed strain monitoring.

7647-119, Session 13c

Mathematical modeling of the SMA-FBG large-strain sensor

D. Li, Dalian Univ. of Technology (China)

A mathematical model of a fiber Bragg grating sensor packaged by shape memory alloy tube is developed in the work. The SMA-FBG sensor with a curved bean configuration is designed to measure large strains. Moreover, the neutral axis of the SMA tube is assumed to bear no the elastic deformation along the neutral axis when pulled or compressed. It is found that the nominal axis strain of the SMA-FBG sensor obeys a parabolic function of the wavelength change of the embedded FBG. Experiments results further verified the theoretical model. Furthermore, dynamic range of the SMA-FBG sensor and its sensitivity are analyzed.

7647-120, Session 13c

A high speed, portable, multi-function, weigh-in-motion (WIM) sensing system and a high performance optical fiber Bragg rating (FBG) demodulator

H. Zhang, Z. Wei, L. Fan, Stevens Institute of Technology (United States); S. Yang, Yantai Univ. (China); P. Wang, H. Cui, Stevens Institute of Technology (United States)

A high speed, portable, multi-function WIM sensing system based on Fiber Bragg Grating technology is reported in this paper. This system is developed to measure the total weight, the distribution

of weight of vehicle in motion, the distance of wheel axles and the distance between left and right wheels. In this system, a temperature control system and a real-time compensation system are employed to eliminate the drifts of optical fiber Fabry-Pérot tunable filter. Carbon Fiber Laminated Composites are used in the sensor heads to obtain high reliability and sensitivity. The speed of tested vehicles is up to 20 mph, the full scope of measurement is 4000 lbs, and the static sensitivity of sensor head is 20 lbs. The demodulator system is packed into a 17" rack style enclosure. The prototype has been tested respectively at Stevens' campus and Army base. Some experiences of avoiding the pitfalls in developing this system are also presented in this paper.

7647-121, Session 13c

Study on the characteristics of wavelet decomposed details of low-velocity impact induced AE signals in composite laminates using fiber Bragg grating sensors

H. Bang, Korea Institute of Energy Research (Korea, Republic of); C. Kim, Korea Advanced Institute of Science and Technology (Korea, Republic of)

Contrary to conventional AE sensors, an FBG sensor has directional sensitivity due to the sensing mechanism and the geometrical shape of an optical fiber sensor. Therefore, in order to use FBG sensors to diagnosis the impact damage on composite laminates, the signal processing method that considers the directional sensitivity of an FBG sensor and attenuation property of AE signals on composites must be developed. Using wavelet transform, we investigated the frequency characteristics of impact induced AE signals focused on the leading wave and chose the key factors to discriminate the damaged condition quantitatively. In this research, we established a damage assessment technique using the change of frequcy characteristics of the wavelet details of AE signal.

In this study, an impact test using FBG sensors was performed to find the signal characteristics of impact induced AE as the different propagation distance and incident angle to an FBG sensor.

Summarizing the results, because the AE signals are largely attenuated in composite materials and the measured intensity of the AE signal is influenced by the incident angle to an FBG sensor, it is hard to evaluate the structural healthiness by only using the intensity characteristics of impact induced AE signals. However, shared portion of the wavelet details is scarcely affected by the signal attenuations and directional sensitivity of a fiber optic sensor. From the reperimental result, we can conclude that using the change of frequency characteristics of wavelet details is a suitable method to detect damage occurrences in composite materials using the fiber Bragg grating AE sensor system.

7647-122, Session 14a

Dynamic characteristics of a thousands-meter scale cable-stayed bridge

J. Liu, Q. Zhang, Tongji Univ. (China)

Nowadays, some dynamic topics have become of increasing concern for the large bridges' safety. However, precise dynamic properties of the bridges are the foundation to solve these topics. In addition, the numerical model can be updated by exact parameters to serve as the baseline model for the following health monitoring and damage detection. This paper describes the experimental and theoretical modal analysis performed on the Sutong Bridge in China, which is the first-built thousand-meter scale cable-stayed bridge in the world. Ambient vibration tests are carried out with dense sensor arrays and the acceleration responses of the deck and the two towers are obtained for processing. Some global vibration modes of the bridge are identified in the frequency range lower than 1.0Hz using both the FFT-based method and the random decrement technique combined with Ibrahim time domain method. The scattering ranges of the extracted modal damping ratios of all modes are narrow and contribute to the following research. Theoretical analysis is conducted on the three-dimentional finite element model developed from the design drawings combined with some measured material properties. A good correlation is achieved between the theoretical and the experimental analysis. So the main assumptions adopted in the FE model for dynamic analysis are assessed and summarized. Based on the study, some useful guidelines for dynamic analysis are presented.

7647-123, Session 14a

Small-format fly-over photography for bridge monitoring

S. Chen, C. Rice, The Univ. of North Carolina at Charlotte (United States); C. Boyle, Boyle Consulting Engineering LLC (United States); E. Hauser, The Univ. of North Carolina at Charlotte (United States)

Current bridge visual inspections are time-consuming, subjective, and rely heavily on personal experiences. The resulting ratings may be inconsistent. This paper discusses using remote-sensing technologies for bridge assessment, specifically, the use of high-resolution aerial imagery. The Small-Format Fly-Over (SFFO) aerial photography is a low-cost solution for bridge surface imaging. Providing top-down views, the airplanes flying at 1000 ft, can allow visualization of sub-inch (< 0.5 inch) cracks and joint openings on bridge decks or highway pavements. A Bridge Surface Condition Indexing (BSCI) technique is presented that provides linear interpretation of cracking density calculations and rating of bridge decks.

Several factors including site lighting, surrounding tree shades and the highway wear surface reflectivity, may influence the quality of the images. Several examples of bridge evaluation using SSFO aerial photography are presented, which demonstrate the capability of commercial remote sensing techniques to serve as effective tools for bridge construction monitoring and condition assessment. The imaging issues associated with SFFO, which include the proper types of analytical techniques that are needed to remove obstructions that interfere with pertinent bridge information, such as crack detection, bridge movement determination, heavy trucking assessment, debris detection, channel width determination and environment assessment.

7647-124, Session 14a

A computer vision-based approach for structural displacement measurement

Y. Ji, Tongji Univ. (China)

Along with the incessant advancement in optics, electronics and computer technologies during the last three decades, commercial digital video cameras have experienced a remarkable evolution, and can now be employed to measure 3D complex motions of objects with sufficient accuracy, which render great assistance to structural displacement measurement in civil engineering. This paper proposes a computer vision-based approach for dynamic measurement of structures. One digital camera is used to capture image sequences of planar targets mounted on vibrating structures. The mathematical relationship between image plane and real space is established based on computer vision theory. Then, the structural dynamic displacement at the target locations can be quantified using point reconstruction rules. Compared with other tradition displacement measurement methods using sensors, such as accelerometers, linear-variable-differential-transducers (LVDTs) and global position system (GPS), the proposed approach gives the main advantages of great flexibility, a non-contact working mode and ease of increasing measurement points. To validate, four tests of sinusoidal motion of a point, free vibration of a cantilever beam, wind tunnel test of a cross-section bridge model, and field test of bridge displacement measurement, are performed. Results show that the proposed approach can attain excellent accuracy compared with the analytical ones or the measurements using conventional transducers, and proves to

deliver an innovative and low cost solution to structural displacement measurement.

7647-125, Session 14a

* Full-scale bridge health monitoring using a receptance-based method

S. A. Jang, S. Sim, B. F. Spencer, Jr., Univ. of Illinois at Urbana-Champaign (United States)

Structural health monitoring has been drawn significant attention in recent decades. To date, a number of structural health monitoring (SHM) strategies have been proposed that can be implemented in smart sensor networks. The stochastic dynamic DLV (SDDLV) method, which is based on the changes in the dynamic flexibility matrix, has been extended for the robust damage localization by employing new damage indices for smart sensor network. In this paper, the extended SDDLV method has been implemented for smart wireless sensor network to enable the decentralized damage localization. The SDDLV service has been combined with basic software and middleware of Illinois SHM toolsuite, to be a complete application from data measurement, system identification, and damage localization and decision assistant for the decentralized wireless sensor application. A long-term structural health monitoring system has been deployed for a full-scale steel truss bridge. The SHM system shows the potential of damage localization system for long-span bridges.

7647-126, Session 14a

US-Korea collaborative research for bridge monitoring test beds

C. Yun, H. Sohn, Korea Advanced Institute of Science and Technology (Korea, Republic of); J. Lee, Sejong Univ. (Korea, Republic of); S. Park, Sungkyunkwan Univ. (Korea, Republic of); M. L. Wang, Northeastern Univ. (United States); Y. Zhang, Univ. of Maryland, College Park (United States); J. P. Lynch, Univ. of Michigan (United States)

This paper presents an interim report on an international collaborative research project between the United States and Korea that fundamentally addresses the challenges associated with integrating structural health monitoring (SHM) system components into a comprehensive system for bridges. The objective of the project is to integrate and validate cutting-edge sensors and SHM methods under development for monitoring the long-term performance and structural integrity of highway bridges. A variety of new sensor and monitoring technologies have been selected for integration including wireless sensors, EM stress sensors and piezoelectric active sensors. Using these sensors as building blocks, the first phase of the study focuses on the design of a comprehensive SHM system that is deployed upon a series of highway bridges in Korea. With permanently installed SHM systems in place, the second phase of the study provides open access to the bridges and response data

continuously collected as an internal test-bed for SHM. Currently, basic facilities including Internet lines have been constructed on the test-beds, and the participants carried out tests on bridges on the test road section owned by the Korea Expressway Corporation (KEC) with their own measurement and monitoring systems in the local area network environment. The participants were able to access

and control their measurement systems by using Remote Desktop in Windows XP through Internet. Researchers interested in this test-bed are encouraged to join in the collaborative research.

7647-39, Session 14b

An optical fiber-based corrosion detection sensor based on laser light reflection

H. Huang, M. Shenoy, The Univ. of Texas at Arlington (United States)

This paper presents the development of an optical fiber corrosion sensor based on the principle of light reflection. The sensor is fabricated with a sensor probe and a sacrificial metallic film welded to a steel tube using laser beam welding (tube/film subassembly). One side of the sacrificial metallic film is exposed to the corrosive environment while the other side is finely polished and isolated from the environment. The sensor probe is used to monitor the reflectivity of the polished side of the sacrificial metallic film. It is packaged with two parallel fibers glued into a seamless steel tube. One fiber is used to deliver light to the polished surface of the sacrificial film while the other fiber is used to collect the light reflected from this surface. Once the corrosion pits, initially formed at the exposed surface of the film, penetrate through the film thickness, the surface reflectivity of the polished surface decreases, resulting in a reduction in the amount of light collected by the receiving fiber. Therefore, a decrease in the intensity of the reflected light serves as an indicator of corrosion development. Since the corrosion sensor detects the corrosion pits only when the corrosion is severe enough to penetrate through the film, the sensitivity of the corrosion sensor is determined by the film thickness. The packaged corrosion sensors are evaluated by submerging them in saline solutions of different concentrations. Experimental results and analysis will be presented.

7647-127, Session 14b

* Luminescent photoelastic coating image analysis and strain separation on a three-dimensional grid

E. Esirgemez, J. P. Hubner, The Univ. of Alabama (United States)

The luminescent photoelastic coating (LPC) technique is a relatively new optical technique to measure the full-field strain on three-dimensional (3D) structural components. A luminescent dye within a photoelastic binder is excited with circular polarized light, and the corresponding coating emission intensity is detected via a CCD camera for loaded and unloaded states. Images are processed to find the relative change in emission with respect to camera analyzer position, and subsequently analyzed to determine maximum in-plane shear strain and the principal strain directions. Image warping methods are implemented to correct the misalignment due to the movement between loaded and unloaded conditions and play a crucial role to obtain accurate measurements. For complex 3D structures with moderate movement or deflection in the field-of-view, especially when implementing an oblique excitation approach to separate the principal strains while accounting for non-strain related polarization changes due to surface inclination, the accuracy and efficiency of the warping methods may not be optimal. Additionally, defining the governing analysis equations, including the surface inclination and strain transformation to separate the principal strains, are not practical for a generic 3D structure. An alternative approach is to perform the analysis on a 3D grid. This study describes such an approach and discusses the analysis procedures to separate the principal strains and to obtain full-field strain distribution on 2D or 3D structures. The theoretical results are compared to experimental data from various tests of 2D and 3D specimens while assessing the accuracy of the approach.

7647-128, Session 14b

Progress on developing acoustic-infrared NDE imaging

X. Han, Wayne State Univ. (United States)

The CAREER project “Investigation of Hybrid Acoustic-Infrared NDE Imaging Mechanisms” has been supported by NSF Civil, Mechanical & Manufacturing Innovation Division, Sensors & Sensing Systems program directed by Dr. Shih-Chi Liu. In the past years, the PIs and

her graduate students have been investigating on several aspects of the innovative Sonic Infrared Imaging technology. Sonic Infrared Imaging is a novel technique implementing the concept of combining infrared (IR) sensing and imaging with pulsed (typically a fraction of a second) sonic/ultrasonic excitation. This technique has significant advantages over traditional NDE techniques as an effective, fast, and wide-area NDE method. The PI has studied the fundamental issues related to this technology, such as heating mechanisms in defects in metal materials and structures through both experimental study and theoretical calculation. The effect of coupling materials that are used to infuse sound energy from acoustic transducer to the target materials/ structures has been investigated. Tools have been developed for signal processing and image processing, and so on. In this talk, the PI will present the progress on their studies of these aspects in the project.

7647-129, Session 14b

Broad-area detection of structural irregularities in composites using fibre Bragg gratings

C. E. Davis, P. Norman, S. D. Moss, Defence Science and Technology Organisation (Australia); C. P. Ratcliffe, U.S. Naval Academy (United States); R. M. Crane, Naval Surface Warfare Ctr. (United States)

The Structural Irregularity and Damage Evaluation Routine (SIDER) is a broadband vibration-based technique that uses features in complex curvature operating shapes to locate damage and other areas with structural stiffness variations. It is designed for the inspection of large-scale composite structures not amenable to more conventional inspection methods. The current SIDER methodology utilises impact excitation at a test mesh and records the response using a small number of accelerometers to determine the operational curvature shapes.

This paper reports on a modification to this technique whereby the acceleration measurements are replaced with in-plane strain measurements using Fibre Bragg Gratings (FBGs). One of the major challenges associated with using Bragg gratings for this type of response measurement is that the strains induced by structural vibrations tend to be low, particularly at higher frequencies. This paper also reports on the development of an intensity-based, swept wavelength interrogation system to facilitate these measurements.

The modified SIDER system was evaluated on an E-glass/vinyl ester composite test beam with a ¼ inch wide notch machined from 25% of it's through thickness. The results accurately detected the presence and location of the notch.

The distributive capacity of FBGs means that these sensors have the potential to replace the excitation grid with a measurement grid, allowing for single point or environmental excitation. The spatially separated measurements of strain can be used to provide the curvature shapes directly. This change in approach could potentially transition SIDER from a routine broad-area inspection tool to an in-service structural health monitoring system.

7647-130, Session 14b

Real time NDE 3D image sensor for harsh electromagnetic environment

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Contemporary CCD image sensors are highly vulnerable even for 0.5 volt EMI fields and highly vulnerable for x-ray and gamma radiation.

The high lever radiation such as 50keV, 100kev, 150keV, 200keV, 300keV, 420keV, is extremely dangerous for human body. CCD image sensors are vulnerable to that radiation level.

We proposed doped single crystal 3D image sensor for the real time NDE measurement.

Proposed sensor was not vulnerable to electromagnetic field produced by High Voltage Tesla generator and to the high level X-ray radiation: 50keV, 100kev, 150keV

200keV, 300keV, 420keV.

Vulnerability and degradation of CCD image sensor to 40keV and 50keV

X-Ray radiation was demonstrated and documented.

Opportunity to use that sensor for real time NDE residual stress and hidden defect measurements of the vital part real engineering construction under high level radiation and EMI fields is discussed.

7647-131, Session 14c

Experimental research on active health monitoring of eccentric compression concrete columns based on piezoelectric wave-theory

S. Yan, Y. Meng, W. Sun, Shenyang Jianzhu Univ. (China)

This paper presents a method for the health monitoring of an eccentric recycled reinforced concrete column embedded in piezoelectric ceramic patches (PZT) based on active wave detection. The experimental system includes a digital signal generator to produce a sweep sinusoidal wave and a digital oscilloscope to receive the signals and a pair of the termed "smart aggregates". One smart aggregate is used as an actuator to generate detecting wave while another is utilized as a sensor to receive the signal. A damage detection method is proposed to identify the cracks of the column by an index composed by the parameters of the waves which have the information of the health and damaged column. The proposed method is established for the statistical damage pattern recognition by wavelet time-frequency analysis and statistical analysis. The level and location of the damage were identified, respectively. The approximate location of the structural damage is determined through the overall detection and the exact location of the possible damage is done through partial identification. The damage patterns and process as well as levels are experimentally monitored and evaluated by the proposed method. The results of the experiment show that the amplitudes of the active monitoring signal produces a large attenuation after the damage and that sweep-wave signal as active health monitoring is effective in identifying the different health status of structure. The statistical pattern recognition algorithm based on wavelet packet decomposition can effectively identify the structural damage.

7647-132, Session 14c

A distributed seismic damage sensing network using piezoceramic-based smart aggregates for RC building structures

S. Hou, H. Zhang, Dalian Univ. of Technology (China)

The seismic damage mechanism remains murky due the lack of the local response record during earthquakes, since the global response monitoring system fails to reveal the local failure modes owing to the high redundancy of building structures. Durable, stable, distributed, low power consumption and low cost are desirable features for the sensors of the structure local seismic damage monitoring, which can not be found in the inventory of conventional sensors. This paper proposed a distributed seismic damage sensing network using Piezoceramic-based smart aggregates for RC building structures, aiming to monitoring the structural local seismic response. The stress history and the crack patterns of the structure in the positions of interest are the two key items to be monitored. During the earthquake event, each smart aggregate of the network works in the way of load cell to record the internal stresses at the pre-designed positions. After

the earthquake, each smart aggregate works as the actuator and exert stress wave in the concrete, and all the other smart aggregates receive the transmitted signals and indicate the damage along the wave propagation path by evaluating the wave energy attenuations. Thus, the crack pattern can be identified.

According to the seismic performance of building structures, prototype tests were conducted to verify the proposed method. The system for monitoring the stress and crack pattern was established. The ability of the smart aggregates in measuring the dynamic load was tested. The excitation frequency of the network for identifying the crack pattern was also optimized. By the preliminary work, it shows that the proposed system has the feasibility to unveil the seismic damage mechanism of building structures.

7647-133, Session 14c

Guided wave-based reference-free crack detection using a single dual-PZT

Y. An, H. Sohn, Korea Advanced Institute of Science and Technology (Korea, Republic of)

Guided wave-based structural health monitoring (SHM) techniques has been widely studied by many researchers. Since guided wave can be changed by environmental effects such as temperature and external loads, the pattern recognition by comparing “current” data obtained from a potentially damaged condition of a structure with the “past” reference data collected at an intact condition of the structure can cause false alarms. To tackle this problem, the authors’ group has been developing new damage detection techniques, which do not require direct comparison with the previously obtained baseline data. Since the reference-free technique does not require the baseline data, this technique may reduce false alarms due to environmental variations. However, the previously developed technique requires two pairs of collocated lead zirconate titanate transducers (PZTs) and relies on the assumption that each pair of PZTs are properly collocated and identical, making it susceptible to varying PZT conditions. The improved reference-free technique presented in this paper overcomes some of these limitations by (1) designing a new PZT called dual-PZT, (2) reducing the number of PZTs from two pairs to one and (3) placing them only to a single surface instead of two. To investigate the robustness against undesirable variations in the system, experimental studies in plate-like aluminum as well as theoretical development and simulations are presented.

7647-134, Session 14c

Time reversal for damage detection in pipes

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Evaluating the integrity of vast natural gas pipeline networks requires continuous and economical monitoring and/or inspection technology. Current approaches for inspecting buried pipelines require periodic excavation of sections of pipe to assess only a couple hundred meters at a time. These inspection systems for pipelines are temporary and very expensive. We propose to use guided-wave ultrasonics with time reversal signal processing methods to develop an active sensing and continuous monitoring system.

The theoretical solution of guided waves in pipes indicates that the pipeline environment is complex due to the presence of multiple modes, multiple paths, and high dispersion. These are usually treated as adverse effects by most conventional ultrasonic techniques. However, time reversal uses the multiple modes, multiple paths, and dispersion to improve damage detection performance. Time reversal is used to focus wave energy across an environment and illuminate changes caused by damage within that medium. Experimental testing on a steel pipe specimen has been performed in pulse-echo mode as well as pitch-catch mode to characterize different damages in pipes. The experimental results show that time reversal gives an improved signal to noise ratio for change (flaw) detection. Finite element simulations are performed to gain insight into ultrasonic guided wave propagation in pipes, and to demonstrate the capability of time-reversal detection for variety of defects. Both the experimental results and simulations show that time reversal provides us with a powerful tool for damage detection in pipelines.

7647-135, Session 14c

Sensor network based pipe-defect imaging and monitoring using guided wave signals

Y. Jin, Univ. of Maryland, Eastern Shore (United States); L. He, Harbin Institute of Technology (China)

Researchers have considered several imaging algorithms for localizing damage in plate-like structures by analyzing the changes in signals recorded from spatially distributed sensor arrays, for example, the delay-and-sum type algorithms and the adaptive MVDR (minimum variance distortionless response) type algorithms. The delay-and-sum type algorithms have poor resolution because of the large sidelobes; while the MVDR type algorithms are sensitive to the mismatch of the weighting function to the true Greens’ function. In this paper, we develop a general framework of imaging and monitoring structure defects for pipes using a spatially distributed ultrasonic transducer network. We focus on two approaches to improve the imaging quality: 1) a better modeling of the defect site and its scattering characteristics; and 2) mode extraction and analysis in response to the defects of interest using the semi-analytical finite element method. By improving the characterization of the scattering of defects, we will show that improved imaging quality can be achieved. Our algorithm will be verified by laboratory experiments.

7647-136, Session 15a

Adaptive backstepping based MR damper monitoring for structural applications

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Magnetorheological (MR) dampers are intrinsically nonlinear devices, which make the modeling and design of a suitable control algorithm for MR damper monitoring an interesting and challenging task [1]. To evaluate the potential of MR dampers in control applications and to take full advantages of its unique features, a mathematical model to accurately reproduce its dynamic behavior has to be developed and then a proper control strategy has to be taken that is implementable and can fully utilize their capabilities as a semi-active control devices.

Most widely used MR damper model is the Bouc-Wen hysteretic model [2]. The parameters of the hysteretic model are usually identified through various pseudo-dynamic testing of the damper. Therefore, dependence of the parameters on damper dynamics (i.e., displacement and velocity) is neglected. Recent studies have shown that this negligence is not minor especially for large MR dampers [3].

The present paper focuses on both the aspects with the development of an adaptive backstepping based nonlinear current monitoring of MR dampers under earthquakes. Adaptive backstepping estimates the MR damper current monitoring directly based on system feedback such that current change in MR damper is gradual. Unlike other MR damper control techniques available in literature, the main advantage of the proposed technique lies in its current input prediction directly based on system feedback and smooth update of input current. Furthermore, while developing the proposed semi-active algorithm, the dynamics of the supplied and commanded current to the damper is considered, which is neglected in earlier studies. The efficiency of the proposed technique is shown taking a base isolated three story building under a set of seismic excitation.

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7647-137, Session 15a

An experimental study of active base isolation control for seismic protection

C. Chang, B. F. Spencer, Jr., Univ. of Illinois at Urbana-Champaign (United States)

Structural control technology has been widely applied to the structural protection against seismic hazards. Active isolation control is one of structural control techniques to enhance the structural performance resisting seismic loadings. The isolation employed at the base of structures naturally increases the structural flexibility but also induces larger base displacement at the same time. Thus the active control is able to reduce the extra base displacement contributed from the isolation devices. The combination of two different control devices creates the possibility of mitigating the base displacement and floor acceleration responses in the mean time. In this study, an active isolation control technique is applied to a six-story steel-frame building model. Three hydraulic actuators with base isolation units are placed at the base layer of the structure along two different directions. The whole system dynamics are characterized through a frequency-domain system identification method. Several control strategies based on the linear-quadratic-Gaussian control algorithm are studied under different environmental setups and different control objectives. Finally, a two-dimensional (2D) control implementation by means of this control system is presented using the shake table test, and the results experimentally demonstrate the realization of a 2D active isolation control system against seismic excitations.

7647-138, Session 15a

Performance of an offshore platform with MR dampers subjected to ice and earthquake

B. Wu, P. Shi, Q. Wang, X. Guan, J. Ou, Harbin Institute of Technology (China)

The environment surrounding offshore platforms is harsh and complicated. As well as erosion from sea water, they may have to endure strong dynamic forces caused by wind, sea wave, sea current, sea ice and even earthquake. Therefore, the structural safety and durability of offshore platforms have raised great concerns of oil industry. In order to suppress the vibration of offshore structures, many control schemes have been studied.

The basic idea in this paper is to insert an isolation layer between the deck and the supporting jacket underneath to suppress the acceleration response of the deck. In the isolation layer, MR dampers were incorporated to dissipate vibration energy and hence control the possible excessive deformation of the isolation layer.

JZ20-2NW offshore platform located in Bohai Gulf of China is the first offshore platform structure incorporating MR dampers in the world. For the semi-active control of MR dampers, the Kalman filter was used to estimate the system state of the platform structure based on the measurements of main deck acceleration and isolation layer deformation. Although the accuracy of the state estimation without any information of external force is not as good as that with the knowledge of its mean value in the case of ice excitation, this has little influence on the control effects. The real-time substructure test (RST) method was employed to investigate the dynamic performance of the platform. The RSTs show that the ice- and earthquake- induced vibrations can be effectively suppressed by the isolation layer with MR dampers.

7647-139, Session 15a

Performance evaluation of shape memory alloy-based rubber isolation systems for seismic response mitigation of bridges

O. E. Ozbulut, S. Hurlebaus, Texas A&M Univ. (United States)

Base isolation is an effective method of reducing seismic response of bridges during an earthquake. Rubber isolators are one of the most common types of base isolation systems. As an alternative to conventional rubber isolators such as high damping rubber bearing and lead rubber bearing, smart rubber bearing systems with shape memory alloys (SMAs) have been proposed in recent years. As a class of smart materials, shape memory alloys shows excellent re-centering and considerable damping capabilities which can be exploited to obtain an efficient seismic isolation system. This paper explores effectiveness of shape memory alloy-based rubber isolation systems for protecting bridges against seismic loads by performing a sensitivity analysis. The isolation system considered in this study consists of a laminated rubber bearing which provides lateral flexibility while supplying high vertical load-carrying capacity and an auxiliary device made of multiple loops SMA wires. SMA device offers additional energy dissipating and re-centering capability. A three-span continuous bridge is modeled with SMA-based rubber bearings. Numerical simulations of the bridge are conducted for various historical ground motions that are spectrally matched to a target design spectrum. Yield strength, yield displacement and prestress level of SMA device and ambient temperature are selected as parameters of the sensitivity study. The variation of seismic response of the bridge with considered parameters is assessed. The results show that the SMA-based rubber isolation system is more effective when the SMA device is prestressed. It is also found that ambient temperature and the yield strength of the SMA device has an important impact on the performance of the isolated bridge.

7647-140, Session 15a

Vibration control and energy harvesting by using an electromechanical tuned mass damper

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Tuned Mass Dampers are simple and very well known devices, commonly used for the passive vibration damping of structures. They are essentially composed of a mass connected to the vibrating structure through a spring and a viscous damper.

Here a new device is proposed, acting much like a classical TMD. It is composed of a pendulum hinged, to the vibrating structure, and an electric alternator, rigidly mounted on the structure itself and connected to the pendulum by means of a rotating shaft and a gear.

Once the pendulum is tuned on a specific structural eigenmode, the structural vibrations make the pendulum effectively oscillating. Due to the pendulum oscillations the alternator rotates and a difference of electric potential arises between its pins. Thus vibrational energy can be dissipated by connecting a dissipative electric load to alternator pins. The proposed device can also be used for energy harvesting purposes, by storing in a battery or using real-time the electric energy generated by the alternator.

An accurate modeling of the coupled system is proposed.

The governing non linear equations are integrated by using a Newmark-type scheme and several numerical simulations are presented, highlighting the main characteristic of the proposed damping system

and the influence of the various parameters entering in the equations on its performances.

Finally, some experimental results are also reported, validating the theoretical model and showing the ability of the proposed device in both vibration damping and energy harvesting.

7647-141, Session 15a

Controllable outrigger damping system for high rise building with MR dampers

Z. Wang, Hunan Univ. (China) and Univ. of Illinois at Urbana-Champaign (United States); C. Chang, B. F. Spencer, Jr., Univ. of Illinois at Urbana-Champaign (United States); Z. Chen, Hunan Univ. (China)

The buildings have continued to soar skyward with the development of material and construction technology. However, flexible structures may fall victim to excessive levels of vibration under the action of wind, adversely affecting serviceability and occupant comfort. To ensure the functional performance of flexible structures, various design modifications are possible, ranging from alternative structural systems and aerodynamic modifications to the utilization of passive and active control devices. One of such structural system is frame-core tube structure with outriggers, which has become a popular approach to improve the efficiency of the core system by simply engaging the exterior columns to aid in resisting part of the overturning moment resulting from lateral loads.

The classical outrigger cantilevering from the core tube or shear wall connected to the perimeter columns directly, which can effectively improve the static lateral stiffness. However, it may not so good for dynamic response. A new energy-dissipation system for such structural system is studied, in which the outrigger and perimeter columns are separate, and vertical viscous dampers are equipped between the outrigger and perimeter columns to make full use of the relative big displacement of these two components. It is expected to effectively improve the dynamic performance of structure at the expense of static stiffness and strength. The modal characteristic of the structural system is theoretically analyzed based on the model with assumed mode method and the simplified FE model by parametric analysis. It is shown that the modal damping of first several modes can increase a lot with optimum viscous damping.

To further improve the control performance of the damping system, semi-active control based on MR dampers is proposed. Based on the reduced control-oriented model form the FE model, linear-quadratic-Gaussian (LQG) control is adopted as the Primary controller. Then, the clipped optimal control is used to decide the voltage command of MR damper as the secondary controller. It is shown that the control performance is quite effective from the numerical simulation. To validate the control performance of semi-active control system, the real-time hybrid testing for this new damping system is undergoing in the Smart Structures Technology Lab in the University of Illinois at Urbana-Champaign.

7647-142, Session 15a

A general numerical solution to optimal nonlinear stochastic structural control problem

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So far, with the development of structural control technology, various kinds of structural damping devices (passive base isolation and/or magneto-rheological dampers) have been integrated with engineering structures to dissipate the input energy under extreme loading conditions. These expendable damping devices, along with the structure itself, will exhibit nonlinear hysteretic behavior to exert the energy dissipation process. Meanwhile, the external input (traffic, wind and earthquake) often takes on random characteristics. Therefore, random vibration of nonlinear hysteretic model has to be investigated to accurately present the structure behavior. In the past three decades, several techniques have been developed and successfully applied to analyze the stochastic dynamics of certain hysteretic models (Wen 1976), among which, statistical linearization (Roberts and Spanos 1990) and stochastic averaging (Caughey 1960, Lin and Cai 1995) are widely applied. However, these methods are usually based on the assumptions of the frequency-band and Gaussianity of responses. Alternatively, active controller design still mainly deals with a linear dynamics assumption (Dyke et al. 1996). Recently, researchers have applied several nonlinear control methods (Yang et al. 1995, 1996), and combined with stochastic averaging method (Zhu et al. 2000), all reported positive results.

In system engineering and applied mathematics, optimal control problem is an on-going research subject. So far, there is no general solution to the optimal feedback control policy. In this paper, by treating the structural system as a nonlinear Markov diffusion process, a general optimal stochastic nonlinear control is presented, for the first time, by invoking the numerical solution to controlled Markov diffusion process. A linear oscillator is chosen as a validation example to show the correctness of the proposed method. In sequel, another example of controlled nonlinear hysteretic one-storied frame under random ground excitation is used to demonstrate the performance of the obtained optimal control.

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7647-29, Session 15b

Novel power transmission methodologies for wireless embedded sensors in structural health monitoring

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Structural Health Monitoring (SHM) techniques focus on assessing the integrity of buildings, bridges, mechanical, and aero-space structures with the aid of sensor technologies and systems. Sensors that are currently being used for damage detection include the traditional strain gauges, piezoelectric wafer sensors, and fiber optic sensors among many others. More recently, there have been growing interests on smart wireless sensors because of their capacity to process data onboard the sensor and then relay that to a central control station wirelessly for decisions. Most smart sensing applications available in the literature locate the sensors outside the structural system due to challenges associated with battery replacement and wireless communications. Cables between sensors inside the structure and the outside units are needed, creating additional elements on the sensing device that can be damaged during construction and decrease the reliability of the instrumentation. This also has the potentials to change

the aesthetics and shapes of some structures. While new research on power harvesting is showing the possibility of embedment of smart sensors in structural elements, such as in concrete girders and piers, knowledge on wireless power transmission and data communication to embedded sensors is clearly lacking to make further advancement in embedded sensor design. This paper presents a summary of the efforts being taken at the University of South Carolina on developing novel closely spaced electromagnetically coupled external and embedded resonant wireless power transmit and receive coils and a dual-function humidity sensor antenna. Both of which are designed for operation when embedded in concrete.

On a system level, an external coil energized by solar energy transmits wireless power at 13.56 MHz to an embedded coil plus voltage multiplier circuit to charge the battery of a sensor. The dual-function sensor can perform the functions of humidity sensing and data communication antenna simultaneously. The dual-function sensor antenna module measures concrete humidity by applying low frequency (1 kHz) fringing electric fields into the sample and then measuring a sensed and amplified signal that reflects any changes in humidity. In the antenna mode the same sensor performs as a data communication antenna at 915 MHz. First, the efficacy of wireless power transmission from the external coil to the embedded receive coil inside a scaled model of a concrete bridge pier will be demonstrated by presenting finite element modeling and simulation results. Simulation results will shed new lights on power transmission efficiency as function of coil geometry, size, concrete thickness, and concrete condition (dry/wet). Second, the performance of the dual function sensor antenna will also be demonstrated by presenting simulation results obtained from Ansoft Maxwell and HFSS (High Frequency Structure Simulator). Results on humidity variation and antenna performance (bandwidth, pattern, and gain) will be presented as function of the variation in the embedding concrete medium.

7647-143, Session 15b

Design of a miniature wind turbine for powering wireless sensors

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In recent years, wireless sensor networks (WSNs) are widely used in different disciplines. Without wire connection, WSNs can remotely access and monitor physical or environmental conditions of the structures. However, the power source of WSNs is usually adopted external chemical battery, which has limited energy density and short life-span, leading to a critical issue of reliable power supply. In this paper, a miniature wind turbine (MWT) system is designed and optimized to harvest continually energy from ambient airflow. Due to the high potential power densities of air flow, using MWT to power the wireless sensor hold promise to integrate energy harvesting techniques from ambient airflow to form a self-powered sensor. To make MWT opeartes at very low air flow rates, a 6.2 cm thorgren plastic Propeller blade is adopted as the wind turbine blade. A brushless DC servomotor with the output power about 1 watt is used as the generator. Meanwhile, MWTs with direct-drive generator and geared generator are fabricated. An equivalent circuit model of the MWT system is established to predict the maximum output power and the optimal resistance load. The performances of the MWT operating at wind velocities of 3 m/s, 3.5 m/s, 4 m/s and with different resistance loads are tested. The equivalent circuit model is demonstrated by the tested results. The initial measured efficiency reaches 9.4% when the MWT operates at the wind speed of 3m/s, which suggest that the MWT can work at very low wind speed in relatively good efficiency. The results also show the MWT with geared generator has a higher open voltage and optimal resistance load but lower maximum efficiency and output power compared with MWT with direct-dive generator. At last, after being adjusted by a rectifier the output voltage is stored into a rechargeable battery to continually power wireless sensors.

7647-144, Session 15b

* Unpowered passive sensor for crack detection and measurement

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This paper presents an unpowered wireless sensor employing dual frequency patch antenna to detect and monitor cracks in metallic structures. The structure under monitoring forms the ground plane of the patch antenna. Crack presence in the ground plane of the patch antenna will cause the corresponding patch antenna resonant frequency to decrease. Thus by monitoring the changes in the resonant frequencies of the patch antenna, quantitative information about the cracks can be obtained.

The crack sensor was evaluated using a Double Cantilever Beam (DCB). An MTS machine was used to apply loads on the DCB beam causing the pre-fabricated crack to propagate towards the patch antenna. The resonant frequencies of the patch antenna were recorded for discrete positions of the crack tip starting from one side of the patch antenna and ending at the other side. A non-contact method to interrogate the antenna sensor was developed to enable wireless transmission of the crack information. An interrogating horn antenna, placed at a far-field distance from the specimen under test, irradiates the antenna sensor with a chirp signal generated by a VNA. The signal backscattered from the patch antenna consists of two major components: the antenna mode containing resonance parameters of the patch antenna and structure mode signal due to reflections from the surrounding structures. The backscatter measurement is processed using a data processing algorithm to isolate the antenna mode component and determine the resonant frequencies of the antenna sensor. Detailed experiment setup, data processing algorithm and measurement results will be presented.

7647-145, Session 15b

Surface acoustic wave devices for wireless strain measurement

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Strain monitoring is a nondestructive inspection method that can reveal the redistribution of internal forces, or the presence of anomalous loadings, in structures. Surface acoustic wave (SAW) devices are small, robust, inexpensive solid-state components in which a wave propagates along the surface of a piezoelectric material, and such devices are used in large numbers commercially as delay devices and as filters. Changes in strain or temperature are understood to cause shifts in the acoustic wave speed, by which such SAW devices can also serve as sensors. We present analytical, FEM simulation, and experimental studies on SAW devices fabricated in our laboratory on lithium niobate wafers, with a typical frequency of 440 MHz established by an inter-electrode spacing of 2 micrometers. We discuss the change in wave speed with temperature and with strain, we outline the influence of rotated cuts for the piezoelectric substrate, and we show results of laboratory sensing experiments. Moreover, an electrode on a SAW device can be terminated as an antenna and interrogated with a wireless RF probe to act as a passively-powered device, and we present laboratory results incorporating such wireless performance in our research investigation. We pattern one set of electrodes on the SAW device as a transducer connected to the antenna, and other sets of electrodes on the device acting as reflectors of the surface acoustic wave. At the microwave frequencies used for SAW devices, it is realistic to use directional antennas on the probe unit to achieve reasonable stand-off distances.

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7647-146, Session 15b

Composite materials with self contained wireless sensing networks

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The increasing demand for in-service structural health monitoring, particularly in the aircraft industry, has stimulated efforts to integrate self sensing capabilities into materials and structures. This work presents efforts to develop structural composite materials which include networks of sensors with decision-making capabilities that extend the functionality of the composite materials to be information-aware. Composite panels are outfitted with networks of self contained wireless sensor modules (wsm) which can detect damage in composite materials via active nondestructive testing techniques. The wireless sensor modules will communicate with one another and with a central processing unit to convey the sensor data while also maintaining robustness and the ability to self-reconfigure when a module fails. Ultimately, this research seeks to create an idealized network that is compact in size, cost efficient, and optimized for low power consumption while providing sufficient data transfer rate to a local host.

7647-147, Session 15b

Detachable acoustic electric feedthrough for power and two-way data transfer

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This paper outlines the development and characterization of a Detachable Acoustic Electric Feedthrough (DAEF) to transfer power and data across a metal (or composite) plate. The DAEF approach is being explored as a potential means of wirelessly powering in-situ structural health monitoring systems embedded within aircraft and other high value engineering assets. The DAEF technique operates via two axially aligned piezoelectric-magnet structures mounted on opposite sides of a plate. Magnetic force is used to align the two piezoelectric-magnet structures, to create an acoustic path across a plate. The piezoelectric-magnet structures consisted of Pz26 piezoelectric disk elements bonded to NdFeB magnets, with a standard ultrasonic couplant (High-Z) used between the magnet and plate to facilitate the passage of ultrasound. Measured impedance curves are matched to modeled curves using the Comsol multi-physics software coupled with a particle-swarm approach, allowing optimized Pz26 material parameters to be found (i.e. stiffness, coupling and permittivity matrices). The optimized Pz26 parameters are then used in an axi-symmetric Comsol model to make predictions about the DAEF power transfer, which is then experimentally confirmed. With an apparent input power of 1 W and 4.2 MHz drive frequency, the measured power transfer efficiency across a 1.6 mm Al plate is ~34%. The effect of various system parameters on power transfer is explored, including bondline thickness and plate thickness. DAEF data communication is modelled using LTspice with three-port one-dimensional piezoelectric models, and experimentally confirmed with early measurements indicating that data rates of 115 kBit/s are feasible.

7647-148, Session 15b

* Infrasonic energy harvesting for embedded structural health monitoring micro-sensors

C. Huang, N. Lajnef, S. Chakrabartty, Michigan State Univ. (United States)

Many signals of interest in structural engineering, for example seismic activity, lie in the infrasonic range (frequency less than 20 Hz). This poses a significant challenge for developing self-powered structural health monitoring sensors that are required not only to monitor rare infrasonic events but also to harvest the energy for sensing, computation and storage from the signal being monitored. Also, constraints on the size of the sensor for embedded operation severely limit the capacity of energy storage and harvesting. In this paper, we show that a linear injection response of our previously reported piezo-floating-gate sensor is ideal for self-powered sensing and computation of infrasonic signals. Our experimental results demonstrate that the sensor fabricated in a 0.5-um CMOS technology can compute and record level crossing statistics of an input seismic event. Collected data are in good agreement with results obtained using a standard data acquisition system. Also, the sensor consumes less than 10 nA of current, which makes its operation based on infrasonic power-harvesting feasible.

7647-172, Session 15b

Feasibility study of wind power generator for wireless smart sensor node in cable-stayed bridge

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Long-term Structural Health Monitoring (SHM) system using wireless smart sensors for civil infrastructures has been investigated by several researchers recently. The wireless smart sensor has a benefit that it can be battery-powered because of its low power consumption. However, in long-term monitoring, this benefit can be reduced by the need of regular battery change. Therefore, considerable attention has been paid to alternative power sources from the environment such as solar power and vibration-based energy harvesting. Another promising alternative ambient energy source might be a wind-generated power; in particular, it can be very useful for structures in windy area such as coastal and mountainous area. In this study, the feasibility of the wind-power generation for wireless smart senor nodes is investigated through experimental and analytical approaches, and the possibility of practical application to actual SHM system of a cable-stayed bridge is discussed

7647-149, Session 15c

* Environmental urban runoff monitoring

B. Yu, P. K. Behera, S. H. Kim, P. Cotae, J. F. Ramirez Rochac, T. Branham, Univ. of the District of Columbia (United States)

The paper presents the project team's integrated sensor-computer sphere technology and proposes to use this technology for real-time and continuous monitoring for waste water runoff at the outfalls (discharge pipes along receiving waters). This project is designed to produce a transformative solution to continuous monitoring of urban waste water runoff for planning and decision making in civil infrastructure, natural environment protection, and water pollution related emergency. The primary idea of the project is a transformative use of accelerometer, programmable in-situ computer, solar power, and wireless communication functions encased in a sealed sphere for real-time and online monitoring of runoff quantity; and the secondary idea is an investigation of transformative applications of the extensible sensor sphere and its attached/compatible sensors for runoff quality monitoring.

The paper discusses the following: (1) how to use the developed sensor sphere for continuous runoff quantity measurement; (2) investigate sensor extensions for runoff quality monitoring; (3) adaptive programming of the sphere for optimal use of power and communication bandwidth for improved cost-efficiency and scalability.

The paper presents important technical feasibility issues and lab test results involved with the functionality of the new sensor unit under real environmental conditions. An exploratory study on how to predict the flow rate versus depth under real situations possibly involving less-than-ideal (i.e., non-circular) pipe shapes, various joint/segment angles, and buildups inside pipes is discussed. The scalability of the potential solutions is another concern to be verified in detail.

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7647-150, Session 15c

* Magneto-inductive waveguide as a passive wireless sensor net for structural health monitoring

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This paper summarizes ongoing work to develop low-cost, wireless, resonant sensor nets that can be used to monitor corrosion in infrastructure systems. A magnetically coupled array of our Electronic Structural Surveillance (ESS) sensors is analyzed using lumped element model. Each ESS sensor is a simple RLC resonator coupled to its next nearest neighbor via a mutual inductance M. A resistive transducer (such as an exposed wire) is used to monitor corrosion. As a threshold sensor, once the transducer opens in response to a certain level of corrosion, this element acts as a defect in the net producing a distinct signatutre. The defect is modeled as a discontinuity in the linear chain representing the net.

We have previously demonstrated that a linear chain (1D array) of ESS sensors behaves as a uniform magneto-inductive (MI) waveguide with a pass band around the resonance frequency of the sensor. The impedance discontinuity due to a single defect leads to MI wave reflection which introduces small ripples in the pass band. For moderately coupled sensors, the insertion loss increases as the defect moves closer to the end of the chain. If a second defect is introduced (corrosion at another location), we observe the two discontinuities act as a resonant cavity producing much larger ripples in the pass band. Hence, a non-intact chain shows an increase in sensitivity compared to the intact chain. The peaks appear when the distance between two defects equals an integral multiple of one half a MI-wavelength and the troughs are spaced a quarter MI-wavelength from the peaks. Also, as the distance between the two defects becomes larger, the number of peak increases. Based on the relationship between the relative positions of two defects and pass band ripples, a technique to determine the location of targets has been developed. Such a non-intact chain/MI waveguide when used for monitoring corrosion in large concrete structures can provide both improved sensitivity and defect location capability.

7647-151, Session 15c

Impedance-based beam damage identification using spectral elements

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This paper presents an impedance-based structural damage identification technique for beam structures using the electromechanical admittance signature records measured from PZT patches. Considering that structural impedance is related to structural physical properties, structure damage can thus be assessed by checking the change of the piezoelectric admittance curves. In this study, a model-based structural optimization method is proposed to solve this inverse mapping problem for structural damage location and severity identification. A numerical study on a simply supported beam is conducted to investigate the effectiveness of the proposed method. The beam is modeled using spectral element which is of high computed efficiency and accuracy in the high frequency range in the numerical study. The influence of measurement noise on the accuracy of structural damage identification is investigated.

7647-152, Session 15c

Detection and assessment of wood decay using X-ray computer tomography

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Towards the evaluation of the minimum amount of wood decay that X-radiography can detect, measurements were carried out using wood specimens prepared following the ASTM Standard Test Method for wood preservatives by laboratory soil-block cultures (ASTM D 1413-99). The wood growth rings of the loblolly pine wood block cubes were relatively parallel to one side of the cubes, i.e., the principal material axis coincided with the geometrical axis of wood block cubes. Seventy block cubes were made, and their original weight, i.e., mass, was recorded. Ten blocks were kept for control and the remaining sixty blocks were exposed to Gloeophyllum trabeum fungus from periods of 1 week to 12 weeks under controlled temperature (27 oC) and humidity conditions (70%). At the end of each for the next twelve weeks, five specimens were removed and their corresponding masses were recorded. X-ray computed tomography (CT) was then carried out. From the CT scans and recorded masses, volumes and densities were calculated. It was observed that significant loss in density, volume, and mass can be associated with increased decay. Blocks exposed to controlled decayed for 12 weeks experienced the most average mass loss (≈40%), average volume loss (≈30%), and average density loss (≈35%). Specimens with one week of exposure to the fungus also exhibited some loss in density (≈2.5%); however, the mass loss was indeterminate due to initial moisture absorption. These results indicate that decay can be detected with x-ray computer tomography as early as one week based on the relative change in local density. It was also observed that decay does not occur uniformly in the blocks; rather, the most decay occurs at the surface in contact with the fungi and it progresses to the opposite surface with continued exposure. For example, blocks subjected to controlled decay for 12 weeks loss 40% of mass density at the surface in contact with the fungus and 30% at the opposite surface, and blocks subjected to only one week to controlled decay experienced 5% density loss at the surface of in contact with the fungus and nearly 0% at the opposite surface.

7647-153, Session 15c

* Experimental demonstration of the AQSSE damage detection technique based on finite-element approach

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It is well-known that the damage in a structure is a local phenomenon. Based on measured vibration data from sensors, the detection of a structural damage requires the finite-element formulation for the equations of motion, so that a change of any stiffness in a structural element can be identified. On the other hand, the finite-element model (FEM) of a complex structure involves a large number of degree-of-freedoms (DOFs), so that: (i) a heavy computational effort is needed to detect the damage, and (ii) a large number of sensors are required. To overcome such a challenge, we propose the application of a reduced-order model approach in this paper. Based on a new damage detection technique proposed recently, referred to as the adaptive quadratic sum-square error (AQSSE), the performance and effectiveness of the reduced-order model approach are demonstrated using large-scale shake table test results recently obtained.

Experimental data from shake table tests for two structures are used, including a 1/4-scaled 6-story steel frame structure and a 1/3 scaled 2-story RC frame. The joint damages in the 6-story steel frame structure were simulated by loosening the connection bolts, whereas the 2-story RC frame was subject to different levels of ground excitations back to back. In the finite-element formulation, the rotational stiffness of joints of test frames was also taken into consideration. For the 6-story steel frame, the reductions of the rotational stiffness at joints due to damages resulting from the loosening of connection bolts were identified based on a limited number of sensor measurements. The continuous degradations of the stiffness in various finite-elements of the RC frame resulting from successive earthquake excitations were also identified. It is demonstrated by experimental results that the proposed damage detection method, based on the combination of the reduced-order finite-element model and the adaptive quadratic sum-square error technique, is very effective for the damage assessment of frame

structures. The method not only can detect the damage locations but also can quantify the damage severities.

7647-154, Session 15c

A study on building an experimental system of PVDF sensor for structural local monitoring on a bridge model

Y. Yu, Y. Wang, Y. An, J. Ou, Dalian Univ. of Technology (China)

Smart material structure originated from aerospace area has been a research hotspot in the application of civil engineering, shipping, and so on. For structural health monitoring of civil engineering, the research about high-performance sensing unit of smart material structure is very important, and this will possibly push further the development of health monitoring and diagnosis technique. As one of the piezoelectric materials belonging to smart materials, PVDF (Polyvinylidene Fluoride) film is widely concerned for its property advantages of low cost, good mechanical ability, high sensibility, resistance of corrosion.

In this paper, for the sake of using PVDF for sensing unit for structural local monitoring of civil engineering, the strain sensing properties of PVDF are studied in detail. The operating mechanism of PVDF is analyzed, and the experimental system of PVDF sensor is integrated with commercial equipments. A bridge model is design and built, and experiments have also been done to study the quasi-static and dynamic strain responding of PVDF sensing element with strain gauge as a reference. The experimental results show that, PVDF is sensitive to the impact response of civil engineering structures, and can finish absolutely the local monitoring in different frequency response cooperating with strain gauge, and the developed experimental system with simple and easy implement can be used for practical monitoring engineering.

7647-155, Session 15c

Experimental research on damage detection of large thin aluminum plate based on Lamb wave

S. Yan, N. Zhao, Shenyang Jianzhu Univ. (China)

This paper focuses on experimental researches on the damage detection of large thin aluminum plate using PZT patches based on lamb wave. An experimental study on the detection of an artificial crack in the aluminum plate is carried out using a wave- based method. The PZT patches are bonded on the surface of the aluminum plate at the given different positions and each PZT is used as an actuator and a sensor simultaneously. An artificial slit with various lengths and the same width is cut during the experiment. The signals with the damage information are compared to the health signal to identify the damage. An energy index in the form of amplitudes of both the damaged and health signals is used to detect the appearance and development of the slit. The time delay caused by the dispersion of the detecting wave for their geometrical difference is used to locate the position of the damage. The wavelet transform using the Gabor wavelet effectively decomposes the differential signal into its time-frequency components, and the peaks of the time-frequency distribution near the center frequency of exciting signal indicate the arrival times of waves. By calculation of time delays between the arrival of the differential and exciting signals, the damage localization points can be obtained. The experimental results show that the proposed method can be effectively used to detect both the level and location of the artificial damage by using the wave-based method.

Conf. 7648: Smart Sensor Phenomena, Technology, Networks, and Systems III

Monday-Wednesday 8-10 March 2010

Part of Proceedings of SPIE Vol. 7648 Smart Sensor Phenomena, Technology, Networks, and Systems 2010

7648-01, Session 1

Interrogation of a wavelength tunable fiber Bragg grating based ring laser for dynamic strain monitoring

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We demonstrate an active fiber Bragg grating based dynamic strain monitoring system that uses the FBG as an optical feedback dielectric mirror in a saturable absorbing fiber loop laser cavity. The laser cavity incorporates an erbium doped fiber loop that is pumped by a Raman laser to generate amplified stimulated emission (ASE) in the C-band, and connected to an FBG allowing for lasing at the center wavelength of the FBG mirror. The fiber laser scheme allows for the generation of high optical powers at the FBG wavelength and narrow spectral line-widths. The laser wavelength can be modulated by quasi-static and dynamic mechanical and thermal strains applied to the FBG, and the laser system is interrogated using a two-wave mixing (TWM) photorefractive interferometer. The TWM interferometer is adaptive to quasi-static spectral modulations, allows for selective demodulation of dynamic FBG spectral shifts, and can be multiplexed for multiple sensor applications. The narrow laser line-width of the fiber laser facilitates long path imbalanced coherent detection of FBG spectral shifts in the TWM interferometer. In this paper, experimental results are presented that detail the detection of acoustic emissions in metal and composite structures using the tunable fiber laser and the TWM interferometer.

7648-02, Session 1

High-speed full-spectrum interrogation of fiber Bragg gratings for composite impact sensing

S. L. Chadderdon, T. Vella, R. H. Selfridge, S. M. Schultz, Brigham Young Univ. (United States); C. M. Park, K. J. Peters, M. A. Zikry, North Carolina State Univ. (United States)

This paper presents a new means for recording detailed strain measurements on carbon fiber composite material structures during impact events. Using a high-speed MEMS filter, and advanced data acquisition card we record the reflective spectral profile from a fiber Bragg grating (FBG) sensor embedded into a carbon fiber composite material. We show that monitoring of the spectral profile at a high repetition rate gives detail on the structural health of the composite that cannot be obtained by only examining the steady state spectrum between impacts, or tracking the position of the spectral peaks during impact. In our approach a broadband spectrum of light is created using an Erbium ASE source and Erbium-doped fiber amplifier. This spectrum is reflected from the FBG sensor, and then directed through a MEMS optical filter and into a photodiode detector. The MEMS filter scans a 10 nm-wide spectrum at 300 kHz, with 60 pm resolution. Typical FBG reflections are around 250 pm wide, and shift during impact by about 2 nm; therefore, the MEMS filter can scan the entire expected range of the sensor, including its complicated sub-structure. The amplified output of the photodiode is recorded with an ADC card at 200 mega samples per second, thus affording a detailed spectral profile during a series of impact events.

7648-03, Session 1

Impact induced damage assessment in composite laminates through embedded fiber Bragg gratings

C. M. Park, K. J. Peters, M. A. Zikry, North Carolina State Univ. (United States); T. Vella, S. L. Chadderdon, R. H. Selfridge, S. M. Schultz, Brigham Young Univ. (United States)

Recently the authors demonstrated full spectral interrogation of a FBG sensor up to 500 Hz while the sensor was embedded in a composite laminate. New signal features were observed in the full-spectral data during low-velocity impacts to the laminate that were not obtainable from peak-wavelength data. The authors speculated that these features could be correlated to the progression of damage in the laminate. In this article we follow the progression of the dynamic full-spectral response of a single FBG sensor embedded in a graphite fiber-epoxy laminate with multiple low-velocity impacts. We compare the unique transient forms of the FBG sensor response to indicators in the laminate global response through the maximum contact force and dissipated energy, previously used to separate the lifetime of the laminate into different damage regimes. It is shown that these damage regimes can be identified strictly from the FBG full spectral response, without the need for information on the loading conditions and global response of the laminate. These measurements demonstrate the richness of information that can be obtained from full-spectral interrogation of FBG sensors in a complex, multiple stress component environment.

7648-04, Session 1

Long range multiplexed sensors based on identical Bragg gratings with ultra-low reflectivity

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Sensors based on the fiber Bragg gratings (FBG) have been recognized to meet well the criteria for structural monitoring of large constructions, leak monitoring systems for long pipelines, etc. Usually, FBGs with reflectivity of about 1% or higher printed in photosensitive or hydrogen loaded fibers are used for sensors. However, for large scale sensor arrays, a “print-cut-and-splice” method of sensor fabrication is very expensive and introduces high total losses in numerous splicing points.

Imprinting on the draw tower or through the protective polymer can provide mechanically durable and low cost sensing fibers containing thousands of identical FBGs in a long single string. However, a reflectivity of Bragg gratings written with such techniques in low attenuation fibers is much below 0.1%.

Here we present a very simple and sensitive technique capable to interrogate ultra-weak Bragg gratings written in a long SMF-28 fiber. The technique is suitable for distributed detection and localization of alarm conditions in early warning systems. Also, a high multiplexing capability was demonstrated in a multi-point measuring system utilizing an array of identical FBGs.

The technique is based on measuring cross-correlation between the probe and reflected signals. A DFB diode laser operating in a CW regime was used as a light source. We present results of experimental verification of this technique in different sensor configurations for static strain and vibration measuring. Multipoint sensor using Bragg gratings with reflectivity of 0.01% printed in a 3-km long fiber was demonstrated. The paper discusses also main features and limitations of the approach.

Conf. 7648: Smart Sensor Phenomena, Technology, Networks, and Systems III

7648-05, Session 2

Acoustic emission measurement with fiber Bragg gratings for structure health monitoring

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Structural Health monitoring (SHM) is a way of detecting and assessing damage to large scale structures. Sensors used in SHM for aerospace structures provide real-time data on new and propagating damage. One type of sensor that is typically used is an acoustic emission (AE) sensor that detects the acoustic emissions given off from a material cracking or breaking. The use of fiber Bragg grating (FBG) sensors to provide acoustic emission data for damage detection is studied. In this research, FBG sensors are used to detect acoustic emissions of a material during a tensile test. FBG sensors were placed as a strain sensor (oriented parallel to applied force) and as an AE sensor (oriented perpendicular to applied force). A traditional AE transducer was used to collect AE data to compare with the FBG data. Preliminary results show that AE with FBGs can be a viable alternative to traditional AE sensors.

7648-06, Session 2

High-precision thermal strain measurements using surface-mounted fiber Bragg grating sensors

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Thermal strain measurements by fiber Bragg grating (FBG) sensors mounted onto different host materials are demonstrated for low coefficients of thermal expansion (CTE). Such low CTEs are typically found in carbon fiber reinforced plastics (CFRP). This work has application potential for FBG sensor networks in the high-precision control of thermal deformations in structures or in curing monitoring. For this purpose, a thermal error model of the FBG sensor, which accounts for the thermo-optic coefficient and the thermal expansion of the FBG, was characterized experimentally. The error-model characterization method is based on reference measurements of FBGs bonded to ZERODUR ceramics. Using this error model, thermal strain can be measured by surface-mounted FBGs on any given host structure using an external temperature reference and the FBG's wavelength shift. This method is demonstrated successfully for unidirectional layers of CFRP with a CTE of -0.4e-6 1/K in fiber direction and for steel (316 Ti), which is commonly used in cryogenic applications. Measurements are performed for temperatures from less than 100 K to more than 450 K and the results are verified by high-precision dilatometer measurements. Accuracy limits of the FBG-based thermal strain measurements are discussed, as well as the minimization of errors induced by the FBG's structural interface. Further, the reduction of errors in the adhesive bonding is discussed. This work expands the understanding of the separation of thermal and mechanical effects in the signals obtained by FBGs.

7648-07, Session 2

Fiber optic thermal health monitoring of composites

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A recently developed technique is presented for thermographic detection of flaws in composite materials by performing temperature measurements with fiber optic Bragg gratings. Individual optical fibers with multiple Bragg gratings employed as surface temperature sensors were bonded to the surfaces of composites with subsurface defects. The investigated structures included a 10-ply composite specimen with subsurface delaminations of various sizes and depths. Both during and following the application of a thermal heat flux to the surface, the individual Bragg grating sensors measured the temporal and spatial temperature variations. The data obtained from grating sensors were analyzed with thermal modeling techniques of conventional thermography to reveal particular characteristics of the interested areas. Results from both front-surface and back-surface heating were compared with the calculations using numerical simulation techniques. Methods and limitations for performing in-situ structural health monitoring were discussed.

7648-09, Session 2

A film pressure sensor based on optical fiber Bragg grating

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The measurement of pressure is essential for the design of wing. In order to measure the surface pressures of the wing, a pressure sensor is installed into a hole on the body surface of the wing. Because limited by the size of the sensor, it can not be applied to a thin or complicated curved body and it's not easy to measure multipoint pressure. In this paper, a novel thin film pressure sensor based on Fiber Bragg Grating is proposed. This thin film pressure sensor can change the pressure into stain of the FBG and the pressure is proportional to the resonant wavelength. The calibration experiment of the sensor was done. The results show the linear relationship between FBG wavelength shift and the pressure. In order to evaluate the performance of the sensor, pressure distributions of a NACA0012 airfoil model were measured in wind tunnel with three film pressure sensors installed at lower camber of it. The measured pressure was compared with calculation results. It's found that the film pressure sensors can well measure the pressure variation on the wing surface for various attack angles.

7648-10, Session 3

Comparing polymer optical fiber, fiber Bragg grating, and traditional strain gauge for aircraft structural health monitoring

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No abstract available

7648-12, Session 3

Embedded fiber Bragg sensors for damage identification in sandwich composites after impact

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Sandwich composites, which are composed of a lightweight, low-stiffness core between two thin composite facesheets, are ideal for applications requiring lightweight structures with high flexural and in-plane stiffnesses. As such, sandwich composites are extensively used in aerospace applications. However these structural components require frequent inspections that are both costly and time consuming, to ensure the structural integrity of the aircraft. Embedded fiber Bragg grating (FBG) sensors have emerged as an alternative to visual and classical NDE inspection techniques. However, it is unknown how effective and durable FBG sensors will be when embedded in sandwich composites subject to low velocity impact. Optical fibers are inherently fragile and it is unknown how well fiberoptic wires survive impact within sandwich composites, even with appropriate coatings Also, the presence of optical fibers within a sandwich composite weakens

the structure of the composite so an optimization must be completed to determine the proper balance between optical fiber density and sensing capacity.

In this paper we investigate the performance of these sensors embedded in sandwich composites considering the above challenges. In particular, we evaluate the spectral response of the sensors as it relates to specific damage modes that are induced during low-velocity impact events. The predicted failure modes from the FBG response are compared to those identified through transient infrared thermography of the same specimens.

7648-13, Session 3

Structural health monitoring of composite laminates using PVDF sensory layer

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Efforts are on in developing structures that can sense and control their own damage by using distributed smart sensors and actuators. A PVDF film can detect changes in composite structures on real time basis with minimum effect on structural integrity. In the present work, 2-D high precision finite elements have been used to analyze healthy and delaminated composite laminate plates with the aim to predict delamination. Flexible PVDF film on the top surface facilitates monitoring of state of health of the laminate on real time basis by producing sensing voltage commensurate to the changes in the stress profile of the structure. Highly convergent 2-D triangular elements with 38 degrees of freedom represent healthy and delaminated composite laminates. A perceptible change in voltage response is seen in the elements with delamination in comparison to the healthy ones. Dynamic responses of composite plates with induced delamination are also studied using Laser Doppler Scanning Vibrometer. Modal parameters such as modal frequency and modal damping of healthy and the delaminated specimens are compared. Applicability of such knowledge for active health monitoring is discussed.

7648-14, Session 4

Multi-axial fiber-optic electric field sensor

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Multi-axial fiber-optic Electric field sensor

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High Powered Microwave weapons use electric fields to overload electronics. We developed a non-intrusive sensor using a previously demonstrated technology based on slab coupled optical sensing (SCOS). Each sensor detects an electric field in direction passing through the slab. By mounting three of these sensors orthogonally to each other, detecting all three axis of the electrical field is possible.

One of the major hurdles of creating a multi-axial SCOS is keeping the size of the sensor small. The size is limited by (1) the size of the sensing material and (2) the bend radius of the fiber the sensor is on. Good sensitivity is attained with SCOS with a length less than 3mm and the D-fiber platform has a small core which allows for much less bending loss than standard single mode fiber. Fibers break when submitted to too much stress. This is overcome by heating the fiber and bending it to relieve the stress on the glass. The small size of the sensor and the ability to bend the fiber allows for small packaging and a small sensing probe.

7648-15, Session 4

Optimization of magneto-mechanical coupling in damage detection using impedance method and magnetic transducer

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Impedance method has been recognized to be sensitive to small-sized damage, as the impedance measurement is extracted at relatively high frequency range. Since the magnetic transducer does not need to have direct contact with the structure surface and can move in the horizontal plane, it is recently employed in the impedance approach due to its capabilities of monitoring the structure with complex geometry and performing multi-site sensing. Compared with the piezoelectric impedance approach, since the coupling between the piezoelectric transducer and host structure is much stronger, the magnetic impedance may be less sensitive to the occurrence of structural damage. Based on a recently developed model of magneto-mechanical coupling coefficient, in this research the coupling between the magnetic transducer and the structure is optimized by carefully selecting the voltage excitation frequency, the sensor location, the distance between the transducer and the top surface of the structure and the number of turns of wire in the electrical coil, etc. The criterion for enhancing the coupling coefficient around single mechanical mode is found to be different from that of multiple modes, and there exists trade-off between different design parameters of transducer. All the observations are verified in the correlated numerical and experimental studies.

7648-16, Session 4

Sensitivity analysis of a smart two-directional MOSFET magnetic sensor

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The full process-compatibility of MOSFET magnetic sensors with CMOS technology allows them to be successfully integrated in electronic circuits and systems to detect the strength of magnetic field and to recognize a magnetic field patterns. However, to accurately characterize the operation and to precisely optimize the structure of MOSFET magnetic sensor, rigorous modeling of their physical properties is required.

The aim of the present work is to develop an accurate physical device simulator that can be efficiently and systematically used to characterize the operation and to optimize the structure of both single and integrated smart two-directional MOSFET magnetic sensors. D.C. and A.C. characteristics of a MOSFET magnetic sensor have been investigated using an efficient two-dimensional physical simulator which directly determines the magnetic field effects on the carrier transport inside the device by an efficient coupling scheme. With the present coupling scheme, the effects of the device geometric parameters, the biasing conditions, and the magnetic field strength on the current deflections on the magnetic sensor relative sensitivity are accurately determined. A smart two-directional MOSFET magnetic sensor structure is suggested to overcome the disadvantages of single MOSFET magnetic sensor. The ability of the present simulator to detect the direction of the applied magnetic field makes it suitable to accurately characterize the suggested smart two-direction MOSFET magnetic sensor from d.c. to microwave frequencies. The suggested sensor is found to have excellent linearity, wide dynamic range of operation, excellent resolution, and sensitivity enhancement without need to scale down the device geometry.

Conf. 7648: Smart Sensor Phenomena, Technology, Networks, and Systems III

7648-17, Session 5

A performance comparison of transducer designs for interferometric and fiber Bragg grating optical accelerometers

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Interferometric fiber optic accelerometers constitute a high-responsivity, high-resolution sensing architecture, with achievable sensitivities of several rad/g and resolutions in the micro-g range, depending on the specific configuration. Fiber Bragg grating (FBG) optical accelerometers offer ease of multiplexing but are inherently less sensitive than their interferometric counterparts. Fiber-based accelerometers have the usual optical advantages of being lightweight, electromagnetically immune, and non-spark emitting over traditional (piezo-electric) accelerometer architectures. Among fiber optic sensing methodologies, both interferometric and FBG accelerometers can be interrogated using phase-based demodulation, which offers advantages over intensity-based sensing schemes such as increased linearity, repeatability, and insensitivity to extraneous measurands.

The performance of an accelerometer is often characterized in terms of its bandwidth, sensitivity, and resolution, all of which depend on the specific transducer design (the mechanical architecture) as well as the optical interrogation architecture. For a given optical architecture, a fundamental tradeoff exists in accelerometer transducer design between bandwidth and sensitivity; attempts to increase bandwidth will generally result in a decrease in sensitivity. This paper investigates the frequency and displacement characteristics that govern this tradeoff for several transducer configurations, in order to determine a pair of configurations that offer the greatest sensitivity for a given optical interrogation methodology (interferometric or FBG), at a prescribed bandwidth. The feasibility of several mechanical architectures is assessed based on the physical dimensions required for a given configuration to achieve a primary resonance of at least 15 kHz. The deflection of those configurations under their own self-weight is then considered a measure of accelerometer sensitivity.

7648-18, Session 5

Development of a wireless 3D digital image correlation sensor for local damage diagnosis

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In this paper, a new wireless sensor network using 3D digital image correlation techniques has been developed for local damage diagnosis. The digital image correlation based optic sensors have been used for measuring full-field displacements and strains of coupon-level specimens mainly in the laboratory setting. However, attempts to use the promising techniques in in-field local health monitoring of structures have been very scarce. To realize this first ever application, a prototypical wireless smart sensing unit consisting of a high performance embedded system, two low-cost CCD cameras, a communication module has been developed. To calculate the displacement field, an efficient image data processing algorithm has been suggested based on the correlations of grey level of subsets and preprocessing of the targeted image. Two different images are taken from two CCD cameras. Before computations of the correlations are carried out in the high performance embedded system, the targeted images are preprocessed to minimize amounts of image data. Displacement fields are wirelessly transferred to a base station for subsequent calculations of the strain fields in the base station. The strain fields are computed in the base station and the data transferred to a RBNB (Ring Buffered Network Bus) data turbine for remote data viewing using RDV (remote data viewer) module. An experimental evaluation of the developed system is demonstrated using a testing setup for metallic materials.

7648-19, Session 5

A wireless strain sensor system

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With the continuous challenge facing the aerospace community in providing globally competitive products, reducing maintenance and ownership costs, increasing aircraft performance, reliability and safety, wireless sensors and sensor networks, particularly self-repairing autonomous sensors networks, are expected to significantly contribute to both legacy and emerging aircraft platforms. These sensors are also expected to reduce the on-going fiscal and operational pressures and provide on-demand decision making capabilities for fleet's life cycle management. While providing additional capability for data, information, knowledge accumulation, decision making and analysis, several issues continue to be in the mind of the end-user as they consider integration of such wireless technology. This paper presents the findings of an experimental investigation of two wireless strain sensor systems, spanning two communication frequencies. Experimental results demonstrated the superiority of the system using the 2.4 GHz range for reduced environmental interferences and the power limitation for both 2.4 GHz and 916 MHz systems.

7648-20, Session 5

Intelligent inventory management for packaged gases

A. A. Mason, A. I. Al-Shamma'a, A. Shaw, Liverpool John Moores Univ. (United Kingdom)

Gas cylinders are used in many different situations, such as in research, in industry, in healthcare, and even in the home. Due to demand in such a wide variety of circumstances, there is the inevitable ambition of gas suppliers to improve the efficiency of their business. To this end, a prototype inventory management has been implemented in order to provide such improved efficiency whilst also integrating sensors in order to monitor gas cylinders from a safety perspective. The prototype system is presented in this paper and its operation described in detail. Preliminary results from the prototype system are also shown and the sensors implemented for demonstration are discussed. Future work to be conducted is also alluded to.

7648-21, Session 6

Advancement of device prototyping and fabrication techniques for sensors and flexible electronics

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The Advanced Materials Branch (AMB) of the U.S. Army ARDEC is developing the capability to custom design, manufacture and integrate novel technologies into functional devices for the creation and advancement of active systems, including printed electronics and sensors. Research being performed will directly and indirectly support the warfighter and allow the DOD to remain at the forefront of active system technologies. Several military programs are developing flexible electronic capabilities for sensing, communication, data collection/storage, and power. Different fabrication and manufacturing techniques are used to develop such systems. In addition to techniques common to the manufacture of microelectronics, MEMS, and the like, the development of nano-inks and related materials printing techniques will revolutionize the manufacture of active systems, flexible electronics, and other custom devices. The shift from typical micro-fabrication

processes, cleanrooms or similar environments, to a material printing process greatly reduces the time and cost associated with device manufacture. The use of advanced materials and material deposition technology on various substrates has allowed AMB to develop several types of printed sensor systems. These sensors are fabricated with both organic and inorganic base materials including polymeric binders, gold, silver, carbon nano-particles. Some of the sensing capabilities include temperature, damage/scratch, flow, pressure, strain, impact, shock, pH, humidity, chemical / biological agent detection, and acoustics. Other sensor capabilities are under development. Customizable devices with various sensing ranges and sensitivity can be modified by varying the sensing element's properties.

7648-22, Session 6

Nanowire-based magnetorheological elastomeric composites for actuators and sensors

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This study focuses on developing and characterizing highly adaptable nanowire-based magnetorheological elastomer (MRE) composites that incorporate ferrous nanowire particles to offer unparalleled control (double that of existing spherical particle MRE formulations) over mechanical properties of advanced sensing and actuation materials. The superior performance of the novel nanowire-based MRE technology will be assessed by implementing the MRE composite in three modes of operation: (1) adaptability of stiffness and damping in actuator by application of magnetic field, (2) sensing of permeability and dilectric constant perturbations in the presence of uniaxial strain, displacement, velocity and pressure fields, (3) collocated sensing and actuation using a self-sensing actuator mode.

Passive elastomeric materials support structures and dissipate energy to reduce

transmissibility of ambient vibration to a structure. Magnetorheological elastomer (MRE) composites enable adaptive control based on controlling apparent stiffness and damping (i.e., semi-active) in response to environmental stimuli based on a feedback signal commanding applied magnetic field. MRE composites are composed of ferromagnetic particles dispersed in solid viscoelastic matrix, where bulk properties depend on dispersant volume fraction (volume fraction), dispersant characteristics (particle

scale, composition, and morphology), matrix material, and magnetic field intensity. MRE composites exhibit multifunctional properties in terms of mechanical and magnetostrictive response, sensing (variable permeability), and actuation. Material synthesis will focus on varying dispersant volume fraction and morphology of ferrous particles (especially nanowires), and scalability of properties with overall sample geometry. Characterization studies examined actuation and sensing as functions of applied stress and

strain, applied magnetic field, dynamic loading with frequency, and temperature effects.

7648-23, Session 6

Self-repairing polymer optical fiber sensor

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In this article we present initial experimental demonstrations of a self-repairing sensor for strain monitoring in extreme loading environments such as impacts. The sensor consists of a polymer optical waveguide which is grown from existing multi-mode silica optical fibers. The sensor waveguide is written and rewritten after damage through the phenomenon of self-writing in UV curable, photopolymerizable resins. A survey of different silica fiber types and input UV intensities are applied to optimize the quality and repeatability of the written sensors. Several challenges are identified in fabricating the original waveguide including the repeatability of the original sensor geometry and the durability of the fabricated waveguide for mounting on a polyimide substrate. The power loss of a lightwave propagating through the waveguide is measured before damage and after damage and subsequent rewriting of the waveguide. This power loss is compared at a variety of applied strain states to determine the strain response and strain range for the original and repaired sensors.

7648-24, Session 6

Embedded high resolution sensor based on optical feedback in a vertical cavity surface emitting laser

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This paper describes the fabrication of a novel type of pressure sensor based on optical feedback in a Vertical Cavity Surface Emitting Laser (VCSEL). The detection mechanism of the sensor is based on a displacement measurement through self-mixing interferometry in a VCSEL. This is observed when a fraction of light emitted from the laser is injected back into the laser cavity by reflection from an external target resulting in a periodic variation of wavelength, optical power, and electrical steering voltage/current, all with period λ/2 (lambda being the wavelength of the VCSEL, typically 850 nm). Using unpackaged laser diodes, one can integrate this sensor in thin optical foils (1 mm thickness). The three unique advantages of this sensor are consequently the sensitivity, the resolution (depending on the pitch of the VCSEL array, typically a few hundred μm) and the embedding possibilities in thin optical foils.

A discrete set-up is developed to provide a proof of principle of this new sensing mechanism: a VCSEL is positioned on a fixed location and a moveable reflector is positioned sufficiently close to the active area. While changing the length of the air gap between the VCSEL and the reflector, variations in both electrical current and optical power are monitored. This set-up has proven the sensing mechanism both in single- and multimode operation of the VCSEL.

When integrating this sensor in a low-cost, polymer optical foil, the external air gap cavity has to be replaced by a thin, compressible "sensor" layer. Mechanical COMSOL simulations to investigate the deformation under pressure for different sensing materials have been carried out and a 100 μm thick, thermally curable PDMS material, Sylgard 184® from Dow Corning has been selected.

The processing of the integrated pressure sensor starts on a rigid FR-4 substrate with a copper layer that serves as a heat sink for the VCSEL. This substrate is covered by an SU-8 layer and a cavity is made by laser ablation to position the VCSEL. After integration of the VCSEL, the sensor layer is applied by spincoating. First characterization tests of this sensor, monitoring both optical power and electrical current, have been carried out.

7648-25, Session 6

Polymer encapsulated 3D sensor arrays as building blocks for creating smart objects

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One of the key challenges in developing effective and scalable technologies necessary to realise future pervasive systems and ubiquitous computing is implementing a methodology that genuinely integrates embedded sensing and processing capabilities with everyday materials and objects. Embedding intelligent systems into polymer materials and using such "smart blocks" for constructing smart objects is a promising way to achieve the above which is far from trivial.

This work provides new solutions to challenges of realising a functional system, comprising sensing, processing and networking components, fully encapsulated in a polymer material. The paper also investigates the possibilities of connecting arrays of these smart blocks in 1-D and 2-D arrangements using an interlocking system that ensures a reliable mechanical as well as electrical connection. The development is split into 3 phases: (1) a dummy package embedded into a polymer block; (2) a dummy package with electronic components and (3) a packaged functional system encapsulated into polymer material. The effects of embedded objects on the host materials are studied and appropriate steps for the design optimisation are taken at each stage of the smart block development. This is done through a detailed finite element analysis (FEM) and mechanical testing. The actual prototypes of smart blocks are created by placing a packaged system (or a dummy in early stages) into a mould, injecting liquid plastic into the mould and curing it. Results on full physical characterisation of the smart blocks and arrays of those will be presented in the final paper.

7648-26, Session 7

SHM process as perceived through 350 projects

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Many structures worldwide are approaching the end of their lifespan and it is necessary to monitor and evaluate their health condition in order to mitigate risks, prevent disasters, and plan maintenance activities in an optimized manner. Structural health monitoring (SHM) recently emerged as a branch of engineering with a great potential for addressing the above mentioned challenges.

In spite of its importance and promising benefits, SHM is still relatively infrequently used in real structures. A possible reason for this is a lack of understanding of the SHM process, which is often considered to be a supplemental activity that does not require detailed planning. However, the opposite is true - only proper and detailed development and implementation of each SHM step can ensure its successful and maximal performance.

The aim of this paper is to present the SHM process through more than 350 projects. Basic concepts are introduced, and the purpose, requirements and benefits of SHM are discussed. The importance of monitoring over a life span is highlighted. Core activities such as creating monitoring strategy, installation and maintenance of hardware, and data management are presented and discussed. The involved parties are identified and their interaction with the monitoring process is analyzed.

7648-27, Session 7

BOTDA sensor testing, data interpretation and evaluation for monitoring in the geotechnical field

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In this paper, an overview of optical sensor testing and evaluation from several geotechnical monitoring projects performed by the authors is given. Additionally, data interpretation for the tested sensors is addressed.

As distributed fiber optic sensing (BOTDA/BOTDR and others) is increasingly applied for monitoring in the geotechnical field, it is crucial to understand the behavior and the limitations of the sensor itself. This sensor can be a bare single mode fiber, but usually the fiber is protected by one or more layers above the fiber, and due to these layers, particularities for each sensor cable exist. So far, no standards and guidelines for fiber optic strain sensing cables are available. In some projects, the selected sensors do not meet the requirements, are inadequate or even break before completion of the integration process. Yet, with a non-ideal sensor, reasonable results can be obtained by suitable data interpretation.

For this paper, the sensor testing consists of straining a section of the sensor to different strain levels and acquiring at each level distributed optical strain data besides independent load and displacement measurements at the sensor cable tip. The optical strain sensing technologies used are BOTDA (Brillouin Optical Time Domain Analysis) and BEDS (Brillouin Echo Distributed Sensing). While BOTDA allows for strain measurements over 1m spatial resolution, the spatial resolution of BEDS is 0.05m. This enormous increase in spatial resolution permits to capture sensor inhomogeneities (e.g. slippage of the fiber within the sensor cable) and therefore, the quality of the sensor evaluation is dramatically improved. For the data interpretation, several known models are summarized and an additional model which includes the above stated slippage is developed. The problems and methods discussed in the paper, as well as the authors approach to testing and data interpretation are expected to be of use for engineers confronted with a fiber optics distributed strain sensing problem.

7648-28, Session 7

Experimental investigation on BOTDA/R-FBG based FRP anchoring pole

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Anchoring pole are the key members of anchorage systems in rock and soil, therefore it is urgent to evaluate the strain states and damage characteristics of anchors to prevent potential risks. However, there is still lacking of an effective technique to measure the strains and damages of anchors due to the complexity and hidden properties of geotechnical engineering. In this study, Two novel types of FRP anchoring poles including non-amplified and local-amplified anchoring poles embedded with BOTDA/R-FBG collinear sensors were proposed and developed, combining the Fiber Bragg Grating (FBG) and full-scale distributed Brillouin Optical Time Domain Analysis/Reflectometer (BOTDA/R) techniques. Two anchorage systems consisting of cement soil body (modeling geotechnical environment), cement mortar body and non-amplified or local-amplified FRP anchor were set up and these anchors were pulled-out in laboratory, respectively. And another two similar anchorage systems were set up to study the creep propertied of FRP anchors at the same time. The strain distribution, strain transmission and damage characteristics of these FRP anchors were investigated comparing the strain measured by the embedded BOTDA/R-FBG collinear sensors with that from traditional strain gauges. The results reveal that the strain measured by embedded BOTDA/R collinear sensors agree well the traditional strain gauges measured values, and their distribution and transmission are consistent in the pull-out and long-term creeping processes. The BOTDA/R-FBG based FRP anchoring poles show the functionality of self-sensing of their strain changes and damage characteristics effectively and are suitable to be applied in long-term structural health monitoring for anchorage engineering.

7648-29, Session 7

Experimental investigation of prestress loss in RC beams

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Prestress loss is a critical issue in structural analysis. Up to date, there are no or few suitable long-term monitoring techniques that can sustain harsh construction conditions. In this paper, six RC beams were tested to prove the concept of prestress monitoring using steel strands with embedded optical fiber sensors. The prestress loss data have been taken by fiber Bragg gratings and optical fiber sensors for three

months. They are compared with those from conventional sensors embedded in smart steel strands. The monitoring results have been analysed and compared with the structural analysis values according to concrete specifications. It was shown that the monitoring data can reveal the entire process of prestress loss during the construction stage and in-service phrase. They agree well with those from the structural analysis, but have higher accuracy than the data from conventional sensors.

7648-30, Session 7

The monitoring of bridges for scour by FBG sensor

H. Jun, H. Dong, G. Zhang, Harbin Institute of Technology (China)

Local scour to the pier footing is one of the most serious factors for the bridge failure. When scouring occurs, the bed materials around the pier footing can be eroded, leaving the infrastructure such as the bridge piers and abutments in an unsafe condition. The common methods are difficult for the real time local sour monitoring because of its bad surroundings. In this paper a new kind of FBG souring sensor for the bridge failure is indicated. The structure of the sensor is optimized by Ansys software. Then groups of experiments were carried out to validate the characters of the sensor. The space resolution of the sensor is up to 0.1m.

7648-43, Poster Session

The feasibility of low power wireless sensor devices in an industrial environment

A. A. Mason, A. I. Al-Shamma'a, A. Shaw, Liverpool John Moores Univ. (United Kingdom)

Whilst many Wireless Sensor Network (WSN) applications remain in the research domain, there is increased effort in some circles to apply the concept and related technology to industrial purposes. This study experimentally tests how low power sensor devices perform in simulated industrial scenarios in terms of communication with a particular focus on metallic environments, where radio frequency devices tend to fare badly. The study covers experimentation in a number of different physical environments, as well as with varying materials which may be found in typical industrial situations. The study also considers two popular operating frequencies for comparison: 915MHz and 2.45GHz. The aim of this study is to gauge the effect that the environment has on a low power sensor device, as this is important when considering their constrained operating parameters. In doing this it will be possible to ensure that WSN are practical for industrial deployment and potentially suggest ways in which improvements could be made.

7648-44, Poster Session

Study on the sensing performance of OFBG under large-scale negative strain

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As a new and sensitive sensing element, OFBG(Optical Fiber Bragg Grating) has been widely used in aerospace engineering and civil engineering. The sensing mechanism and properties have been widely studied by lots of researchers, but the sensing properties of large negative strain of OFBG are still destitute.

In this paper, with the aids of large shrinkage performance of PP(polypropylene) during its curing, we gained about -13000 με's strain changes by embeding bare OFBG inside the PP bar to study the sensing properties of OFBG in this strain level. The results show that OFBG can remain its sensing properties well---- linearity, repeatability and form of centre wavelength are both reasonably. And the strain sensitivity coefficient of PP-OFBG is about 0.85pm/με, this is very near with that of calculating results considering strain transmission between PP and OFBG. Which are all helpful and useful for further use of OFBG in other applications.

7648-45, Poster Session

Simple expressions of the reflection and transmission coefficients of a lamb wave by a rectangular notch

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The scattering of Lamb waves by a two-dimensional rectangular notch is investigated for rapid inspection of defects in a structure. To derive the reflection and transmission coefficients of the scattered waves in a simple way, the scattering caused by the notch is analyzed by combining data from the study of individual scattering processes. Linear equations corresponding to the reflection and transmission coefficients are constructed along with scattering graphs. For an illustration of the efficacy of the presented method, the scattering of fundamental Lamb waves is inspected according to the depth and width of a notch in a plate. Validity of the new analysis method was confirmed by comparing the calculation results with those from FEA of the same plate and notch configurations. These showed excellent agreement with each other.

The analysis scheme utilizing the scattering graphs and the simple equations developed in this paper, allows quantitative examination of the characteristics of Lamb waves scattered by a defect, in a much simpler manner with greater rapidity and ease than traditional methods. The technique is applicable to assess the health of a structure for ultrasonic nondestructive testing purposes. The same scheme can be extended to analyze the effects of multiple notches of different geometries on the reflection and transmission of Lamb waves.

7648-46, Poster Session

The application research of wireless networks for HSM

J. X. Wang, G. Huan, Y. Song, Xiamen Univ. (China)

The traditional wired structural monitoring systems often suffer of various problems mainly related to the cabling which limits their applicability. These issues include the cost of cables, their difficulty of installation, their invasive effect on the monitored structure, their vulnerability to mechanical damage, and the high cost of maintenance. All these disadvantages urge the need for wireless monitoring.

Most of the current wireless SHM systems are mainly based on single-hop, and the network can only support a small number of nodes. For the realization of multi-hop, low complexity and low power requirements, we introduce a system based on ZigBee protocol built on the IEEE802.15.4, then design and implement the corresponding hardware and software of wireless sensor. The desired features are validated by experiments, including relatively high network capacity, low power consumption, and moderate data rate.

In this paper, the work mainly consists of five parts:

1) Summarize and analyze the domestic and foreign state-of-the-art of WSN for SHM.

2) Design and realize wireless sensor nodes, including the signal conditioning module, data collection module, data storage processing module and wireless transmitter module based on the ZigBee protocol.

3) Based on the applications of the structural health monitoring, design the corresponding network topology, design the finite-state machine of the application program, and realize the software.

4) Test the performance of the system, including hardware, software and network.

5) Conclude the work of this thesis and envision the future work.

Conf. 7648: Smart Sensor Phenomena, Technology, Networks, and Systems III

7648-47, Poster Session

Dynamic forces measurement of cables in structural health monitoring

Y. Song, Xiamen Univ. (China)

The cable plays a more and more important role in civil engineering domain recently. As an effective construction member, cable is used in many long-span spatial structures. The cable tension measurement is required in the construction control, assessment and long-term monitoring of cable-supported structures. How to get an accurate cable tension not only in a static situation, but also in a dynamic circumstance has received much attention over the years. Apart from the electromagnetism sensor technology which is still in study, the vibration-based cable tension evaluation theory plays an important role in cable tension test. Mostly, the detection uses the Fourier Transform to get the frequencies of the cable, and then applies the vibration-based cable tension theory to evaluate the cable tension.

Moreover, as a conventional method for cable tension measurement, the Fourier Transform can only be used in the static cable tension force test, but not dynamic cable tension test. Recent years, the study on cable properties under lord traffic has gained more and more attention. The cable dynamic tension describes the load-deformation behavior of cables subjected to dynamic loading. It represents the intrinsic dynamic properties of cables. In this paper, wavelet transform tool that has the time-frequency analysis ability is used to analyze the signal, and obtain the cable tension dynamic change along with the time.

7648-48, Poster Session

Distributed structural damage detection technology with smart sensor network

Y. Lei, Xiamen Univ. (China)

Distributed Structural Damage Detection Technology with Smart Sensor Network

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ABSTRACT

Numerous methods of structural damage detection have been proposed; however, there are great challenges in the detection of structural local damage in large size structures by the conventional strategies with densely distributed sensors and central acquisition of a tremendous amount of data. Recently, a novel method has been proposed by the authors to detect structural local damage in large size structures subject to some unknown excitation based on substructure and distributed computing strategy. The proposed structural damage detection algorithm is suitable for implementation on a network of densely distributed smart sensors based on their distributed computing capacities. In this paper, application of this method with experimental verification for distributed damage detection of large size structures based on a new smart sensor network is studied. The sensor network recently by the authors has a two-level cluster-tree architecture. A large size structure is divided into substructures. The distributed sensors in a substructure are grouped into a cluster. A cluster head is assigned to each cluster to coordinate the sensor nodes in its cluster and to collect the measured data from the sensor nodes. The algorithm for structural damage detection is embedded into the on-board computational core of each cluster head in the sensor network for the detection of local structural damage in different substructures concurrently with parallel computing or even independently. Considering the practical case that measurements at the substructure interface are not available, a cluster head in a substructure is communicated with limited information those in the surrounding substructures. The damage detection results in the substructures are then sent back to the central station. To assess its efficacy in practice, the new technique is experimentally verified by employing a truss structure in this paper. Performance of proposed technique is illustrated by detecting the local damages through the decrease of the element stiffness. It is shown that the proposed technique provides an efficient and practical tool for detecting structural local damage in large size structures.

Keywords: damage detection, distributed computing, substructure approach, smart sensors, wireless sensor network, experimental verification

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7648-31, Session 8

Piezoelectric wafer active sensor guided wave imaging

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Active sensing methods use actuators/sensors permanently attached to the structure, to generate the guided wave and measure the arrival wave at sensors propagating through the structures. The damage diagnosis is performed through the examination of the arrival waves carrying structural features. Since direct sensory data in guided wave interrogation are implicit with damage related information, advanced signal processing is necessary to extract damage related features for damage diagnosis. Array signal processing is an approach that can map the structure being interrogated with propagating guided waves, giving a visual indication of damage presence, location, size, and orientation for crack damage. The arrays can be configured with sensors separated from each other and used in pitch-catch mode.

In this paper, we first studied guided wave excitation on isotropic plates and the capability to use piezoelectric wafer active sensors to selectively excite a certain mode in the structure. Then several algorithms for imaging with the sparse arrays working in pitch-catch mode were developed. The algorithms were applied to isotropic specimens including thin aluminum plates with hole and crack damage, and thick steel plates with crack damage. The resolution (minimal detectable damage size) was also investigated and compared to the resolution of a linear PWAS phased array. Image post processing was used to generate binary image of the scanning result and yield an estimation of the damage size. Application of this PWAS guided wave imaging to composite structures will also be discussed.

7648-32, Session 8

A comparison of 3 optical systems for the detection of broadband ultrasound

G. J. Thursby, B. Culshaw, Univ. of Strathclyde (United Kingdom)

There are many applications of ultrasound in the field of material properties' evaluation and structural health monitoring. Here we will consider the detection of broadband laser generated ultrasound and acoustic emission as simulated by the pencil break test. In this paper three optical methods of detecting these ultrasound signals are compared; these are polarimetry, fibre Bragg gratings and vibrometery. Of these the first two involve the bonding of a fibre sensor to the sample, whilst the vibrometer is a non-contact instrument that measures out-of-plane displacements. FBGs respond to the in-plane strains associated with an ultrasound wave whilst the polarimeter is sensitive to birefringence produced by pressure waves acting normal to the fibre. The sensitivities and bandwidths of the systems are compared and their relative merits are discussed. It will also be shown that the polarimetric responses of symmetric and antisymmetric Lamb waves differ, which opens up the possibility of learning more about the nature of an acoustic signal using this technique than can be determined simply from the measurement of in-plane or out-of plane displacements. The practicalities of implementing the different systems will also be discussed.

Conf. 7648: Smart Sensor Phenomena, Technology, Networks, and Systems III

7648-33, Session 8

Fatigue crack location and quantification in lug joints using reference-free methods

S. O. Soni, S. B. Kim, A. Chattopadhyay, Arizona State Univ. (United States)

The work focuses on fatigue crack characterization in two dimensional structures using a reference-free method. It is seen in structures with complex geometry, separation of symmetric and anti-symmetric modes becomes difficult and hence damage characterization using conventional guided wave studies cannot be used directly. Also, conventional methods rely on knowing a baseline/reference state to carry out damage detection. In many practical applications, the environmental conditions in which a structure is operated do not remain same over time. Sensor signals, thus, collected for the damaged state cannot be compared directly with the baseline because a change in the signal can be caused by several factors other than a structural damage. It therefore becomes essential to devise a reference free damage detection scheme to better estimate the current state of the structure. In this paper, a reference free technique for detection, location and quantification of fatigue cracks in lug joints is demonstrated. Experiments will be carried on lug joint samples prepared from Al 6061 plate with 0.25" thickness. These samples will be instrumented with piezoelectric transducers on both surface at similar locations and tested under fatigue loading of 350lbs - 3500lbs in an Instron fatigue testing frame. Crack lengths will be monitored over the entire fatigue life with a CCD camera and ARAMIS, a non-contact optical 3D deformation measuring. Sensor measurements will be made for every crack length. These sensor signals will be decomposed into the fundamental modes and the components of these waves undergoing mode conversion from the crack tip will be utilized to determine the extent and location of the crack.

7648-34, Session 9

Comparison of guided wave sensors for SHM sensor networks

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The need for custom-designed sensor networks, tailored to the specific SHM task for practical application of guided waves, is constantly growing. As a prerequisite for a successful development of different monitoring concepts the transducers wave excitation and receiving properties has to be known. The more exactly they are understood the more reliable monitoring concepts are possible. Nowadays different piezoelectric transducer concepts with varying acting principles having their specific advantages are used in SHM application and are revealing strongly unequal properties concerning source density and directivity patterns. These transducer types are compared with respect to the efficiency to excite and receive guided waves. Furthermore a reciprocity-based model for the estimation of the maximum Transducer-to-Transducer distance is introduced and applied.

7648-35, Session 9

Flexible ultrasonic transducers for structural health monitoring of metals and composites

M. Kobayashi, C. Jen, K. Wu, S. E. Kruger, National Research Council Canada (Canada)

Thick (> 40 μm) piezoelectric films were coated directly onto titanium and polymer composite membranes of less than 100 μm thick by a sol-gel spray technique. With the addition of top electrodes made of silver paste they serve as flexible ultrasonic transducers (FUTs). At room temperature, the ultrasonic signal strengths of the developed FUTs made of lead-zirconate-titanate composite (PZT-c) films can be at least the same as those of the commercially available broadband UTs centered at 5 - 10 MHz. Special glues as ultrasonic couplant between the FUT and the external surface of the structures made of metal and graphite/epoxy composite were used for on-site installation. The developed FUTs can easily accommodate various transducer arrays by simply choosing different top electrode configurations. Ultrasonic thickness and guided wave measurements of parts with curved surfaces using these FUTS are demonstrated at temperatures up to 150°C. Use of this technology for health monitoring of structures is discussed.

7648-36, Session 9

Thin film characterization using high frequency eddy current spectroscopy

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For launching quickly new processes introduced by nano science into much more conventional industrial applications, robust and economical reasonable inspection methods are required for process control and quality assurance. Due to the complexity of processes e.g. for thin film coatings or nano engineered materials, variations of material parameters like microstructures, grain boundary conditions, particle or void density etc. can occur by minor shift of process parameters. Coming from high tech industries e.g. semiconductor and solar industries the methods available for thin film characterization and quality control are complex and often require scientific skilled personal. The established methods for non destructive testing of materials and structures are not fulfilling the postulated requirements of modern materials modified on the nanoscale. This paper presents first results obtained by a new developed high frequency eddy current spectrograph on thin film coatings and crystalline materials.

7648-37, Session 9

A physically based classification approach for identifying acoustic emission source mechanisms

M. J. Sundaresan, D. Rajendra, A. C. Esterline, North Carolina Agricultural and Technical State Univ. (United States)

Acoustic emission (AE) based structural health monitoring technique has the potential to monitor and size damage growth in critical structural elements. However this technique is hampered by the presence of extraneous signals that are currently difficult to eliminate and result in unacceptable levels of false positives. An additional limitation of the AE based technique is the difficulty in assigning individual AE waveforms to the corresponding damage mechanism. Past efforts in identifying extraneous noise signals were based on conventional AE parameters such as overall frequency, amplitude, and rise time. Such features are not completely satisfactory for eliminating false positives in practical situations.

Damage growth in structures usually result in large numbers of acoustic emission signals, typically ranging up to tens of thousands of waveforms during a laboratory test. The shape and duration of acoustic emission waveforms are affected by various factors such as the type of damage growth, geometry of the specimen, relative positions of the AE source and the sensor. The presence of different Lamb wave modes, reflections from the boundaries, frequency dependent attenuation, and sensor resonance characteristics alter the waveform. Hence it is difficult to identify the source mechanisms from the shape of the waveforms, especially when many mechanisms are simultaneously active. Numerical simulations of different types of AE sources in real structures have become possible and the information gathered from these simulations can greatly aid in the understanding of AE signatures commonly encountered in experiments.

In the present paper, both experimentally generated acoustic emission waveforms and numerical simulations were used for developing the pattern classification procedure. The specimen considered for this

purpose are 2024 T3 aluminum panels with central crack subjected to fatigue loading. Acoustic emission signals associated with fatigue loading were examined. The panels' dimensions were 12" wide, 24" long and 0.125" thick. The waveforms starting from initial location near the center of the panel to locations near the ends were tracked. The numerical simulations included through the thickness crack, part through cracks, and fretting related acoustic emission signals. The influence of the sensor characteristics were incorporated into the analysis.

The acoustic emission waveforms were processed to extract important features that are related to the source mechanism responsible for the AE signals. The features that are considered are the relative magnitudes of symmetric and antisymmetric modes, relative arrival times of these modes, the frequency content of individual modes, components that are due to reflections from the boundaries, and the components introduced into the sensed signals by the sensor characteristics. After the features were extracted from the waveforms, classification algorithms including K-means clustering, and self organizing maps, were used to identify the different source characteristics. This classification procedure was able to differentiate different types of source mechanism. Such techniques can be used to detect and eliminate extraneous sources of acoustic emission signals.

7648-38, Session 10

Bayesian probabilistic structural modeling for optimal sensor placement in ultrasonic guided wave-based structural health monitoring

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Many optimal sensor placement methods for structural health monitoring establish performance metrics based on the detection of a limited set of damage states and locations. In guided wave-based inspection however, monitoring is carried out over a continuous region, with a continuous distribution of possible damage locations, types, sizes, and orientations. Here, traveling waves are excited and then sensed by a set of transducers with the intent of detecting and localizing previously unobserved scattering sources which are associated with damage. To measure sensor network performance in this application, we implement a Bayesian experimental design approach by computing the total posterior expected cost of detection over the entire monitoring region. Since the optimization usually must be carried out using a computationally expensive meta-heuristic such as a genetic algorithm, efficient modeling of the interrogation process is key to solving this distributed sensor placement problem.

In this work, we implement a previously developed semi-analytical modeling approach for wave scattering within our Bayesian probabilistic framework in order to optimally place active sensors for detecting cracks of unknown location, size, and orientation. This involves assuming a set of a prior probability distributions on the three unknowns and defining spatial distributions of cost associated with type I and type II detection error. These parameters are driven by the geometry, material, in-service structural loading, and performance requirements of the structure. Through a set of sensor placement examples, we demonstrate how changes in the probability and cost distributions can dramatically alter the optimal layout of the transducer network.

7648-39, Session 10

Optimal sensor placement on a composite wing

C. K. Coelho, A. Chattopadhyay, Arizona State Univ. (United States)

The research proposed in this paper focuses on optimizing sensor placement on a composite wing. The composite wing will have a uniform cross section based on the NACA0012 airfoil. The wing is constructed using unidirectional carbon fibers in a [0/90]2s configuration and has a rectangular cross section with a 12" chord length and 38" span. The test specimen will be fixed in a cantilever position and weights may be added to simulate its static loading. Piezoelectric transducers will be used as the sensors and actuators in this optimized sensor network because they are cheaper and light weight compared to conventional transducers.

Experiments will be carried out to quantify the attenuation of a 4.5 cycle burst wave as a function of frequency and direction on the composite plate. The optimal sensing radius as a function of position on the wing will also be studied. Once this information has been calculated, it will be implemented into a finite element model in ABAQUS using NASA's MAC/GMC. The model will simulate an actuator excitation on the composite wing and a virtual sensor response will be collected at every node in the finite element mesh.

This information will then be analyzed for sensor sensitivity analysis uses a distance based outlier technique developed by NASA called Orca. The sensor sensitivity of each sensor calculated captures the sensitivity of the sensors over a specified length of time. This provides added information regarding the sensor behavior for the current damage state. The results of this analysis can also help establish the size of the smallest damage that can be detected using a given excitation signal. Next, an optimization algorithm will be developed that takes the information about the sensing radius and the sensor sensitivities at every point and maps out the optimal location of sensors on the structure for sufficient overlap and sensor redundancy.

7648-40, Session 10

The role of embedded sensors in damage assessment in composite laminates

C. M. Park, S. Xu, K. J. Peters, M. A. Zikry, North Carolina State Univ. (United States)

Fiber Bragg grating (FBG) sensors can be easily embedded in composite laminates for high quality damage identification due to the close location of the sensors to the damage sites. While embedded strategies can be applied that reduce the impact of the presence of sensors on the response of the host material system, such as multiplexing and proper sensor alignment, this negative affect cannot be entirely removed. The goal of this project is to design a sensor placement optimization strategy based on the identification of damage features through the response of embedded FBG sensors while incorporating strength reductions due to host-sensor interactions. These strength reductions are calculated through a combined experimental-numerical research effort. We predict local strain field perturbations in heterogeneous materials due to the presence of embedded sensors and verify these through the collection of data on global composite laminate response and property degradations for various embedded sensor densities.

7648-41, Session 10

Adaptive agent population management using evolutionary algorithms

B. Chen, W. Liu, Michigan Technological Univ. (United States)

This paper presents an evolutionary algorithm for the agent population management in agent-based distributed sensing and monitoring systems. Adaptive agent population management is important since the size of the agent population can be critical to balance the monitoring requirement and system's resource. The small size of agent population may cause undetected anomaly, while the large size of agent population will over-consume system's resource.

The presented agent population control approach employs evolutionary algorithms combining with the knowledge of monitoring systems. The global knowledge is used to select agents, determine lifetime parameter, and maintain sufficient diversity for exploring unknown conditions. A case study is presented in the paper for the application of

this evolutionary algorithm to manage the agent population in a mobile agent-based structural health monitoring (SHM) system. In this mobile agent-based SHM system, the active structural health monitoring is performed by a group of mobile monitoring agents equipped with damage pattern recognition algorithms. The mobile agents patrol the structure and recognize damage patterns using the dynamic response data of the structure. For the adaptive agent population management, parameter control mechanisms of the evolutionary algorithms incorporate system knowledge to change values dynamically. For example, when a specific damage pattern is detected, the reproduction rate of the mobile agent that has high fitness with the detected damage will increase. Agent life is defined by a parameter, lifetime. After creating a mobile agent, it is assigned to a specific lifetime value to control the death of the agent.

7648-42, Session 10

Global management of smart structures in distributed systems

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A universal solution for nonlocal management of smart structures in distributed systems is offered. It is based on establishing “overoperability” layer consisting of dynamically networked intelligent modules interfaced with usual devises (sensors, robots) throughout the structures of concern. This forming a parallel interpreter of high-level Distributed Scenario Language, DSL, in which any structure analysis, simulation, global-goal pursuit, and self-recovery are formulated in a concise form. Starting from any component, the scenarios can cover the system at runtime, in viruslike mode, without central resources. Self-evolving scenarios can be hidden throughout the structures as “recovery genes” or injected from outside in unexpected situations. DSL is based on waves-like, gestalt-related, space-grasping formalism allowing us to express distributed solutions on a semantic level, often on the fly, much simpler and shorter than by agents-based approaches, shifting usual management routines (like partitioning into components, their communication and synchronization) to effective automatic interpretation. This has been tested on numerous distributed applications including classical graph and network problems, knowledge bases, virtual reality, simulation of battlefields, crisis management, cooperative robotics, and electronic warfare. Public domain (from the language originally called WAVE, developed under Siemens) has been used in different countries (mainly for network management and media networks investigation).

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Conf. 7649: Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security IV

Monday-Thursday 8-11 March 2010

Part of Proceedings of SPIE Vol. 7649 Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security 2010

7649-01, Session 1

Simultaneous strain and temperature monitoring of a small-scale steel column in harsh environment with long-period fiber grating sensors

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Up to date, it is still a challenge to simultaneously monitor the strain and temperature of a steel structure in a fire environment. Most of the current sensors cannot survive high temperature and harsh environment. Strain data under high temperature conditions are critical to the understanding of structure behaviors in fire applications. In this study, a novel long period fiber grating (LPFG) sensor written with a CO2 laser is designed and investigated for a simultaneous measurement of strain and temperature, simulating a fire environment. Its performance is evaluated with the testing of a small-scale steel column under compression. Both steel yielding and potential buckling at high temperature are studied. The LPFG sensor has two separate groups of gratings in series, which correspond to the measurements with two cladding modes such as LP05 and LP07. The sensor is protected from high temperature and ambient refractive index change effects by encapsulating it into a glass tube. Preliminary tests indicate that the LPFG sensor exhibits negative and positive strain sensitivity coefficients with cladding modes of LP05 and LP07, respectively. Its temperature sensitivity remains positive for both cladding modes. As such, one measurement with a single optical fiber can give rise to both strain and temperature values that are crucial to the understanding of temperature-sensitive structural behaviors. Experiment results also show that such an encapsulated sensor is more sensitive than a bare LPFG sensor to temperature up to 700°C.

7649-02, Session 1

Damage localization on a composite wing using FBG strain amplitude information

C. Hiche, C. K. Coelho, A. Chattopadhyay, Arizona State Univ. (United States); M. E. Seaver, U.S. Naval Research Lab. (United States)

Structural Health Monitoring (SHM) is currently a critical research area in the aerospace industry. Successful implementation on a large scale depends on the reliability and accuracy in assessing the structural health of a given structure, so that predictions can be made regarding its remaining useful life. Fiber Bragg Grating (FBG) sensors satisfy the current SHM framework requirements due to their low weight, minimal space requirement, capable of sustaining harsh environments, are unaffected by electromagnetic interference, can be multiplexed, and can be used both passively or active with the use of piezoelectric transducers

The present study will provide an accurate method for impact localization on a composite wing structure using a FBG sensing network. Impact damage will be induced in the structure and the damage location will be calculated by analyzing the strain amplitude information of a FBG network. An efficient localization model based on the difference in strain amplitude will be developed to locate damage. The model will be validated experimentally using two different types of composite wings, hollow and foam core. Both wings will have a NACA0012 airfoil and made of 4 unidirectional carbon fiber plys in a [0,90]s configuration. The wings will be impacted at different energies to assess the minimum energy required for an accurate prediction of damage localization. Also, the effects of the impactor on damage localization will be investigated, using a hemispherical and conical impactor tip. An array of FBG's will be surfaced mounted at different locations throughout the span of the wing. The FBG sensors will be located at different angles with respect to the chord length (across and along the chord length) to assess the effects on the strain amplitude response of the FBG.

7649-03, Session 1

Fiber optic acoustic emission sensor for damage monitoring in composite tube

A. Nguyen, Los Gatos Research, Inc. (United States); A. S. Rakow, Exponent, Inc. (United States)

This paper presents results from the development of a structural health monitoring system for composite structures which consists of fiber optic acoustic emission sensors interrogated using a laser demodulation technique. Using a laser frequency tracking technique to interrogate Bragg grating fiber optic sensors, high frequency acoustic emissions emanating from damage in a composite tube under loading can be monitored with high sensitivity. The Bragg grating sensors and interrogation device can be permanently surface mounted on composite structures for non-destructive testing or on-line damage monitoring applications. Results are presented from a validation test which included a woven carbon fiber composite tube in four-point loading outfitted with fiber optic acoustic emission sensors in addition to piezo-electric sensors and actuators used in a pitch-catch ultrasonic monitoring scheme. Results show a good correlation between acoustic emission counts, relative change in ultrasonic sensor signals, and damage in the tube under increasing load.

7649-04, Session 1

Risk of infrastructure performance failures

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Writers propose to define risk due to infrastructure performance failure as:

RISK = $\eth$ (α β * P [Hazard] * P [Failure to Perform|Hazard] * γ δ Cost)

P [Hazard] = Probability of occurrence of an event that may trigger failure

P [Failure to Perform|Hazard] = Probability of failure to perform, given a specific hazard

Cost = Consequences of failure to perform including opportunity cost

$\eth$ = Reflects the epistemic uncertainty governing the evaluation of risk

α = Factor based on the nature of a hazard or event triggering failure

β = Psychological impact factor - reflecting tolerance to risk

γ = Duration of exposure - minute, day, year, decade, lifetime, forever

δ = Cultural factor - Adjustment for how infrastructures are regarded by different cultures

This conceptual equation for risk was motivated by the authors' experience that indicates risk cannot be estimated in absolute terms, and risks due to the failure of infrastructures are perceived in a relative manner by different individuals or cultures. Risk due to infrastructure failure should be compared and ranked with risks due to other hazards such as war, epidemic, recession, etc. Such an analysis would help make decisions for resource allocation to various needs and concerns at the state and national levels.

The authors' interest in the proposed definition of risk comes from their observation of how different societies and cultures appraise and embrace their infrastructures and regard the engineers responsible

with the performance of infrastructures. The differences in a society's esteem of civil engineers may be related to the risks posed by infrastructure failures under various limit events. Societal factors also dictate the threshold of infrastructure conditions and performance levels for which a society would demand improvement. For example, while it is possible to observe many highly deteriorated and debilitated bridges in the USA, this is not the case in many European countries. Data suggests that average annual probability of bridge collapses in the USA is ~1/10,000 while this may be ~1/100,000 or less in Germany, France, Austria and Switzerland. Based on their risk tolerance, as well as cultural reasons, various countries naturally spend different portions of their GDP on the condition evaluation, preventive maintenance, repair and retrofit of their infrastructures. One may consider that the lesser risk of infrastructure failures in Europe may be due to lower probability of destructive natural hazards in many European Countries. However, in the case of Japan, it is exposed to far greater hazards than the USA, but, based on the authors' experiences, its infrastructures are far better designed, inspected, evaluated, maintained and retrofitted, which produces a lower risk of failure relative.

The authors hope to initiate a discussion regarding the risks we accept as a society in relation to infrastructure performance failures as well as the strategies that we may leverage to reduce and mitigate such risks. Although many assume that we may rely on innovative technology to help reduce cost and improve performance, in the authors' experience such expectations may be realized only if technology is developed, demonstrated and applied in an integrated and coordinated manner. Paradigms such as performance-based engineering, asset management and health monitoring should be leveraged as the intellectual framework for infrastructure technology development and the paper will offer an overview of these paradigms.

Finally, the authors would like to discuss an apparent lack of policy and guiding strategies for infrastructure preservation in conjunction with coordination and standards for validation and demonstration of new technology in the USA. This is of great concern, since without legislative and federal government efforts towards a national infrastructure policy it may not be possible for federal, state and local agencies to develop effective strategies for technology selection, validation and integration standards. We recall how Germany rebuilt the East, and how many Eastern European Countries have brought their infrastructure up to common standards. We also recall how Japan rebuilt its entire infrastructure following the Kobe Earthquake. It appears that while the U.S. citizenry may well be impressed by the quality of infrastructures in most of Europe and Japan, they have implicitly accepted a lower standard for their domestic infrastructures.

The authors propose forming a grass roots coalition from academe, government and industry within ASCE to link/integrate their efforts with those of Building America's Future (http://www.ens-newswire.com/ens/jan2008/2008-01-22-02.asp) and other worthy and a-political alliances in order to establish the critical tenets of policy, strategy and technology for effective infrastructure preservation. The integration of the resources of agencies such as NSF, FHWA, NIST, US Army Corps and others, including participation from Europe and the Far East is needed to help develop the policies, strategies and their proper implementations for properly addressing risks posed by infrastructures.

7649-05, Session 2

Development of visibly active titania-CNT films for low-light sensors

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Damage associated with composites systems can lead to catastrophic and expensive failures due to non-value added inspection processes in industry. Industry and research have no single inspection technique used on its own to provide reliable real-time and cost effective results. The answer may lie with the development of SHM systems (TriP) by the use of triboluminescent crystals, as well as comparable transport mechanism embedded or incorporated throughout the entire composite structure that relies on a phenomenon known as "Photocatalysis".

In recent work, Triboluminescent (TL) materials (ZnS: Mn phosphors) have shown to be compatible in composite matrices to utilize their inherent luminescent properties for potential structural health monitoring capabilities. Incorporation of Triboluminescent materials into composites raised many important problems involving extraction of TL emissions and sensory capabilities. This work examines the use of TL crystals embedded in the composite matrices to act as indicators of localized damage. These crystals react to straining or fracturing by emitting light of varied luminous intensity, giving an indication of crack initiation well ahead of catastrophic failure(s). Initial testing has shown that light can propagate through doped resins alone, as well as doped fiber reinforced plastics (FRP) laminates with material transparency being a major hindrance. Because of the opaqueness of the most composite systems, a novel extraction method is being assessed for ballistic transport capabilities. Titanium dioxide has come under extreme scrutiny for its stable composition and photocatalytic abilities and might prove useful as ab initio sensor realization for light extraction.

7649-06, Session 2

Field investigation on casing pipe damage for pumping well pipelines using optical fiber sensors

Z. Zhou, Harbin Institute of Technology (China); G. Chen, Missouri Univ. of Science and Technology (United States)

Large field investigations and theoretical studies show that casing damage is closely related to seepage field change. Therefore it is significant to monitor a pipeline's stress state and evaluate the safety of its casing pipe. To date, no cost-effective and reliable sensor exists for long-term monitoring and evaluation of casing, and no satisfactory sensor installation technique has yet been developed. Further, traditional casing inspection techniques cannot provide a real-time monitoring and warning system for casing damage. This paper provides a technique for real-time monitoring of casing safety based on an optical fiber sensing technique. This approach combines a distributed Brillouin sensing technique for distributed strain measurement and a fiber Bragg grating (FBG) sensing technique for local high-precision strain measurements. This work developed along smart fiber-reinforced polymer (FRP) rebar containing an embedded optical fiber with no solder joint to measure the distributed strain of the casing pipe, and it investigated the sensor installation techniques. The results of field experiments show that both the FBG sensors wrapped in epoxy resin and glass cloth and smart FRP rebar can survive the casing down hole, withstand a harsh service environment, and deform with the casing pipe. The FBG strain sensors effectively reveal the strain state for the hot spot of casing pipe at each warning stage, and the optical fiber in FRP provides full information on strain distribution in the casing pipe. The maximum relative variance of strain between the FRP rebar and the FBG strain sensor was about 10%.

7649-07, Session 2

In-situ monitoring of curing and ageing effects in FRP plates using embedded FBG sensors

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Fiber reinforced polymer (FRP) composites have been widely applied in civil engineering in recent years for retrofitting, renewal of existing structures and building completely new structures or components. The lack of the durability performance data of FRPs under severe service conditions, however, adversely affects the wide and safe application. In the present study, fiber Bragg grating (FBG) sensors were embedded in glass-, carbon- and basalt-fiber reinforced epoxy based FRP plates with wet lay-up technology, to in-situ monitor the stain changes in FRPs during the curing, and hygrothermal and freeze-thaw ageing processes. The study demonstrates that the curing of epoxy resin brings in a slight tension strain (e.g., ~50με) along the fiber direction

and a high contraction (e.g., >900με) in the direction perpendicular to the fibers, mainly due to the resin shrinkage. The cured FRP strips were then subjected to distilled water immersion at various temperatures and/or freeze-thaw cycles from -30oC to 30oC. Remarkable strain changes of FRPs especially due to the variation of the temperatures during freeze-thaw cycles indicate the potential property degradation due to fatigue. Progressive increase of the residual strain after freeze-thaw cycles reveals the occurrence of debonding or delamination of the FRP plate, while the expansion of the water immersed FRP indicates the swelling effect due to the water uptake. Based on the monitored strain values with temperature change and water uptake content, CTE (coefficient of thermal expansion) and CME (coefficient of moisture expansion) of the FRP plates are exactly determined.

7649-08, Session 2

Smart fiber reinforced plastic composites based on fiber optic sensing

C. Yang, Z. Wu, Y. Tang, Southeast Univ. (China)

Smart fiber reinforced plastic (FRP) composites have attracted worldwide attention in recent years. In this paper, the development and application of smart CFP composite based on fiber optic sensing is briefly reviewed. The FRP composite is characterized by excellent mechanical property and long-term durability, suitable for structural engineering. The structural elements are the reinforcing fibers and polymers, and the active elements are optic fibers. The active optic fibers may be optic FBG sensors or traditional optic fibers, which are characterized by a high sensing accuracy and dynamic measurement; while, the traditional optic fibers analyzed with Brillouin scattering techniques are characterized by a distributed and continuous sensing. They can be used in many engineering fields, such as aerospace and civil engineering.

7649-09, Session 2

Stay cable live load effects analysis by embedded OFBG sensors

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Stay cables are some of the most critical structural components of a bridge. However, stay cables readily suffer from fatigue damage, corrosion damage and their coupled effects. Thus, health monitoring of stay cables is important for ensuring the integrity and safety of a bridge. Glass Fibre Reinforced Polymer Optical Fibre Bragg Grating (GFRP-OFBG) cable, a kind of fibre Bragg grating optical sensing technology-based smart stay cables, is proposed in this study. For the smart stay cables, three Glass Fibre Reinforced Polymer (GFRP) bars embedded with Optical Fibre Bragg Grating optical (OFBG) strain and temperature sensors were inserted into the hollows of steel wires and fixed with the steel wires at the anchorages of the cable. Therefore, the GFRP-OFBG bars can consistently deform with the steel wires in a cable and that the smart stay cable can sense its own strain the temperature. The fabrication procedure of the smart stay cable was developed and the self-sensing property of the smart stay cable was calibrated. The application of the smart stay cables on the Tianjin Yonghe Bridge was demonstrated and the vehicle live load effects smart stay cables were evaluated based on field monitoring data. Furthermore, the probability distribution and extreme value distribution of live load effects of the stay cables were established. Finally, the fatigue load effects of smart cables and fatigue accumulative damage of the smart stay cables was evaluated based on field monitoring strain.

7649-10, Session 3

Condition based fatigue life estimation of a cruciform structure under biaxial flight profile loading

S. Mohanty, A. Chattopadhyay, Arizona State Univ. (United States)

The present paper proposes a hybrid system identification and data mining approach for real time residual useful life estimation of an Al-2024 specimen subjected to biaxial flight profile loading. The current damage state will be estimated using real-time sensor measurements and system identification approach such as correlation analysis. The correlation analysis will be a multidimensional correlation analysis considering measurements from different sensors. In addition contrary to the conventional correlation analysis multidimensional information fusion will be performed in a high dimensional kernel space. The kernel transformation will be helpful to separate the nonlinear damage features from ambient and input dependant noise, otherwise it would be difficult to do so using the conventional linear correlation analysis. Once the current damage state is estimated from real-time sensor measurements, the future state will be predicted using real-time state update from the system identification model, anticipated future loading information and using a Bayesian statistics based data mining approach. The condition based prognosis approach will be used to estimate residual useful life in real-time and will be validated under random biaxial flight profile loading.

7649-11, Session 3

Damage detection in z-pin reinforced co-cured composite Pi-joints using Lamb wave propagation using 3D laser vibrometry

H. Kapoor, Virginia Polytechnic Institute and State Univ. (United States); E. D. Swenson, S. R. Soni, Air Force Institute of Technology (United States)

Pi-Joint test specimens are designed to replicate a co-cured, all composite skin-spar joint within a wing structure. These joints exhibit various complex damage modes and thus, require better understanding of damage detection for structural health monitoring purposes. This paper presents the application of 3D laser vibrometry for damage detection in z-pin reinforced co-cured composite pi-joints by Lamb wave measurements. At present, there is no existing literature for damage detection in pi-joints using 3D Lamb wave propagation. In the experimental set up, Lamb waves would be excited using one PZT actuator and the time velocity signal would be measured. 3D measurements would include both the in-plane and out-of-plane velocity data through which A0 and S0 modes would be measured separately. The extent and location of damage would be quantified from Lamb wave interaction with the damage. And,3D Laser vibrometry amplitude response would be compared with amplitude response from undamaged specimen and with the response from PZT based pitch-catch sensor arrangement. Sensitivity analysis with respect to damage would be performed for various input parameters.

7649-12, Session 3

Understanding Lamb wave propagation in confined geometry using 3D laser vibrometry

H. Kapoor, Virginia Polytechnic Institute and State Univ. (United States); E. D. Swenson, S. R. Soni, Air Force Institute of Technology (United States)

This paper would present the understanding of complicated physics involved in Lamb wave propagation in confined sample geometries like co-cured composite DCB and pi-joint specimen and the effect of z-pin region and different lay-ups and thickness variation in skin, flange and

web of pi-joint on Lamb wave propagation, using 3D laser vibrometry measurements. 3D laser vibrometry is a non-contact method of generation and reception of 3D Lamb waves using piezo-sensors. 3D Lamb waves in these specimens, besides involving different mode generation and mode selection, would also involve active interaction with the geometric boundaries. Further, the application of fundamental modes requires understanding of dispersion properties, which is again a complex phenomenon, especially in composite materials and in such confined/complex geometries. This paper would study the wave interaction behavior due to boundary reflections and dispersion characteristics of Lamb waves in co-cured composite DCB and pi-joint specimens. 3D measurements would include both in-plane and out-of-plane velocity data measurements, which are important from the point of view of understanding A0 and S0 modes. This work would be the only effort to date in developing an understanding in 3D Lamb wave propagation in confined sample geometries.

7649-13, Session 3

Characterization of the self-sensing performance of carbon nanotube-enhanced fiber-reinforced polymers

B. Loyola, V. La Saponara, K. J. Loh, Univ. of California, Davis (United States)

The increased usage of fiber-reinforced polymers (FRP) in recent decades has created a need to monitor the unique response of these materials to impact and fatigue damage. As most traditional nondestructive evaluation (NDE) methods are ill suited to detecting damage in FRPs, new methods must be created without compromising the high strength-to-weight aspects of FRPs. This research examines the use of multilayered carbon nanotube (CNT)-polyelectrolyte (PE) thin films directly deposited onto woven glass fiber fabrics to form a self-sensing FRP material. CNTs are initially suspended in polyanionic poly(sodium 4-styrene sulfonate) (PSS) solution and layered alternately with polycationic polyvinyl alcohol. By repeating the layer-by-layer (LbL) bilayer fabrication process 5o to 100 times, a homogeneous and piezoresistive CNT-PE nanocomposite is deposited onto the woven glass fabric. The thin film and fiber fabric are used as-is for wet lay-up fabrication of FRPs and to simultaneously encode self-sensing capabilities within the bulk composite. In this study, the electromechanical response of the self-sensing composite is evaluated using a high-precision TestResources load frame. The composite is subjected to complex load patterns while its electrical properties are characterized via electrical impedance spectroscopy (EIS). In addition, resistor-capacitor equivalent circuit models will also be derived for describing the piezoresistive performance of the proposed self-sensor.

7649-14, Session 3

Analysis methods for eddy-current imaging of carbon fibre materials

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Carbon fiber materials in lightweight composites get more and more important in many applications. Unlike to metal, the technological parameters and certificated quality control mechanisms have not been developed yet. There is no testing system for a cost efficient, reliable or real non-destructive inline inspection available. Downstream manual inspection operations of the Raw Carbon Fiber materials (RCF) and the post laminated Carbon Fiber Reinforced Plastics (CFRP) are only certified with water coupled ultrasonic methods by the aircraft industry.

Based upon the multi-frequency Eddy-Current device, developed at Fraunhofer IZFP, structural and hidden defects such as missing carbon fiber bundles, lanes, suspensions, fringes, missing sewing threads, angle errors and delaminations in this very low conductive material are detectable with this eddy-current technique. Due to the use of optimized sensors and intelligent image analysis methods the complex impedance signal can be allocated to different carbon fiber layers in RCF and CFRP. This technique allows the detection of defects in the depth of the composite as a function of the sample thickness and resin volume. The dimensions of the smallest detectable defects are in the range of a few millimeters depending of the detection depth and sensor size.

Algorithms and eddy-current C-Scan image-processing techniques for carbon fibre material testing are described in this paper.

7649-15, Session 3

NDT of carbon nanotube reinforced composite using electromagnetic techniques

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The CNTs properties have inspired interest in using CNTs as a filler in polymer composite systems to obtain ultra-light structural materials with enhanced electrical, thermal and optical characteristics. In particular, industry recognizes many potential applications such as electrostatically dissipative materials and aerospace structural materials . Even though the carbon nanotubes hold much promise for many applications, there are several unresolved questions. The major problems are related to the distribution of the CNTs in the matrix and the adhesion between the nanotubes and the matrix.

Since the efficiency of CNTs as reinforcement filler for the polymer composite matrix, depends on the dispersion level of the CNT into the matrix, it is important to characterize and quantify the nanotubes distribution within the matrix. Moreover, the electrical properties and the thermal diffusivity of reinforced polymer composite are affected by the distribution of CNTs into the polymer matrix. Therefore, techniques capable to detect the electrical conductivity and thermal diffusivity response of the nanocomposites (i.e. eddy current method and lock-in thermography (LT)) could be useful to detect the state of dispersion of CNTs within the insulating polymer matrix on large macroscopic scale.

The aim of this work is to demonstrate the capability of the eddy current method based on HTc SQUID and lock-in thermography to acquire information on the distribution and the uniformity of CNTs within an insulating polymeric matrix on macroscopic scale.

7649-16, Session 4

An overview of civil infrastructure critical national need in the NIST Technology Innovation Program

H. F. Wu, National Institute of Standards and Technology (United States)

The Technology Innovation Program (TIP) at the National Institute of Standards and Technology (NIST) was established for the purpose of assisting U.S. businesses and institutions of higher education or other organizations, such as national laboratories and nonprofit research institutions, to support, promote, and accelerate innovation in the United States through high-risk, high-reward research in areas of Critical National Need (CNN). Areas of Critical National Need are those areas that justify government attention because the magnitude of the problem is large and societal challenges that need to be overcome are not being sufficiently addressed. TIP seeks to fund transformative research targeted to address key societal challenges. Funding selections are merit-based. This paper provides an overview of the recent two-year solicitations of the Civil Infrastructure critical national need.

In FY 2007, Civil Infrastructure together with Manufacturing, Energy, Green Technologies, Healthcare, Networks, and Water were identified

as seven interesting CNNs in the NIST Technology Innovation Program. An area of the Critical National Need in Civil Infrastructure was selected in June 2008 and a solicitation with the title "Advanced Sensing Technologies for the Infrastructure: Roads, Highways, Bridges and Water Systems" was launched as the inaugural investment ($9 million in the first-year for new awards) for the NIST Technology Innovation Program in FY 2008 Competition. This competition has resulted in nine new awards in which TIP has committed $42.5 million and $42.6 million cost-share is from industry/university-share for the next five years. The Civil Infrastructure Part II CNN was selected in March 2009, and with the title of "Advanced Sensing Technologies for the Infrastructure: Water Systems, Dams, Levees, Bridges, Roads, and Highways". The FY 2009 Competition was solicited with $10 million for new TIP awards. The second round Civil Infrastructure CNN solicitation emphasized repair/retrofit materials and application technologies. It is anticipated that this Competition will be completed by November 2009. The selected FY 2008 nine awards and to-be-selected TIP new awards from the FY 2009 Competition are high-risk and high-reward research. The research will specifically address societal challenges in the area of structural health monitoring for advancing the state-of-the-art and contributing to the U.S. science and technology base. The research will also provide an endorsement of ensuing transformational results that will benefit the Nation.

7649-17, Session 4

Advances in civil structural health monitoring with optical fiber sensors

F. Ansari, Univ. of Illinois at Chicago (United States)

The origins of optical fibers go back to mid 19th century when the scientists tried to guide, bend, and transmit the light from one location to another. Now, optical fibers have found widespread usage in telecommunications as well as in medical and sensing applications. This presentation provides a summary review of principles involved in sensing with optical fibers and specific methods more prevalently employed in industrial applications. In particular, the focus will be in the specific applications of fiber optic sensors to civil structures.

7649-18, Session 4

Overview of a novel cyber-enabled wireless monitoring system for health management of bridges

J. P. Lynch, Univ. of Michigan (United States)

The long-term deterioration of large-scale infrastructure systems is a critical national problem that if left unchecked, could lead to catastrophes similar in magnitude to the collapse of the I-35W Bridge. Fortunately, the past decade has witnessed the emergence of a variety of sensing technologies from many engineering disciplines including from the civil, mechanical and electrical engineering fields. This paper provides a detailed overview of an emerging set of sensor technologies that can be effectively used for health management of large-scale infrastructure systems. In particular, the novel sensing technologies are integrated to offer a comprehensive monitoring system that fundamentally addresses the limitations associated with current monitoring systems (for example, indirect damage sensing, cost, data inundation and lack of decision making tools). Self-sensing materials are proposed for distributed, direct sensing of specific damage events common to civil structures such as cracking and corrosion. Data from self-sensing materials, as well as from more traditional sensors, are collected using ultra low-power wireless sensors powered by a variety of power harvesting devices fabricated using microelectromechanical systems (MEMS). Data collected by the wireless sensors is then seamlessly streamed across the internet and integrated with a database upon which finite element models can be autonomously updated. Life-cycle and damage detection analyses using sensor and processed data are streamed into a decision toolbox which will aid infrastructure owners in their decision making.

7649-19, Session 4

Multi-functional engineered cementitious composites for intelligent infrastructure

V. C. Li, J. P. Lynch, Univ. of Michigan (United States)

This paper describes the concepts of a multi-functional cement based composite designed for intelligent reinforced concrete structural applications. This smart Engineered Cementitious Composite (ECC) possesses a high damage tolerance behavior to extreme loading, rendering infrastructure safety significantly beyond the current generation of concrete materials. In addition, the smart ECC is designed to exhibit simultaneous self-healing and self-sensing ability. This means that under damaging load, the material will recover its mechanical properties without human intervention. Further, the self-sensing functionality enables the material to self-inspect its own condition of damage and recovery. As a result, smart ECC provides a platform to create the next generation of civil infrastructure that are virtually collapse resistant while possessing autogenous healing of damage and autonomous health monitoring intelligence. Some preliminary results in the development of smart ECC will be presented.

7649-20, Session 4

Smart antenna technology for structural health monitoring applications

T. Ozdemir, Y. Goykhman, L. M. Oberdier, Monarch Antenna, Inc. (United States); J. P. Lynch, Univ. of Michigan (United States)

A 4"x4" planar smart antenna has been developed for structural health monitoring. The antenna is based on Monarch's GEN 2 self-structuring antenna (SSA) technology and provides polarization-diversity and beam-diversity for improving signal-to-noise ratio (SNR). Both polarization-diversity and beam-diversity have been documented in the literature to be cost-effective strategies for improving SNR. The antenna works with the Narada sensing and data collection platform developed at the University of Michigan for structural health monitoring applications. A microcontroller constantly monitors the RSSI and starts searching for a better antenna beam if the RSSI falls below a threshold. Each beam provides a minimum of 2dBi gain, and is selected by applying appropriate DC voltages to the RF switches on the aperture of the antenna. Beams are divided into two groups of two, each group offering vertical or horizontal polarization. The motivation behind the antenna was to improve the point-to-point RF link gain by 1dB and achieve a minimum of 90% packet success at short distances of 100ft. Field tests are ongoing (on test bridges) and results will be presented at the conference as to packet delivery rate increase (averaged over time and use cases) when compared to a monopole. Also presented at the conference will be the improved gain of the same antenna printed on a thicker substrate, which is also an ongoing effort.

7649-21, Session 4

Near-optimal sensor placement for health monitoring of civil structures

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An important task in implementing health monitoring of civil structures is determining the number and locations of the sensors, leading to several approaches to Optimal Sensor Placement (OSP). As part of a multi-disciplinary project to develop wireless monitoring systems for our national infrastructure, we plan to implement health monitoring systems for a long-span and a short-span bridge, in collaboration with the local Department of Transportation. These systems will include both fatigue monitoring and damage detection. In this paper we focus on OSP for output estimation based continuous health monitoring using three approaches. The first aims to minimize the static estimation error

of the structure deflections, using the linear stiffness matrix derived from a finite element model. The second approach aims to maximize the observability of the derived linear state space model. The third approach aims to minimize the dynamic deflection estimation error using a Linear Quadratic Estimator. In general, OSP approaches lead to nonlinear mixed-integer optimization problems. A local optimum can always be found using an incremental search algorithm. Approximate solutions can be obtained via relaxation to a convex optimization problem. Both nonlinear mixed-integer and relaxed convex optimization formulations of the proposed approaches are presented, and applied to a model of the long-span New Carquinez Bridge in California. The resulting sensor placements as generated by the three methods are evaluated by applying displacement estimation on simulated sensor data for several load cases. Additionally, the computational requirements and convergence results are compared and discussed.

7649-22, Session 5

Nondestructive monitoring of a pipe network: hydrodynamics and model experiment

M. Shinozuka, P. Chou, Univ. of California, Irvine (United States)

An innovative method of identifying the location and extent of pipe damage in a network of pressurized pipeline system such as a water distribution network is developed. The method utilizes the non-invasive measurement of the acceleration on the pipe surface using a wireless network of MEMS-based accelerometers installed at each node of the water system network. When a rupture occurs in the network, the sudden change in the water pressure propagates through the network and induces corresponding change in the acceleration of pipe vibration. This change in the pipe acceleration is measured, and on the basis of these acceleration data, the pipe damage can be found in the pipe between the two end joints where the acceleration changes form local maxima. This parallels to the observation, demonstrated by analytical simulation of transient flow, that the damaged pipe is found between two end joints where the water pressure gradient form local maxima.

This will replace the effort of water pressure monitoring with acceleration monitoring on pipe surface where the latter is significantly more acceptable by the industry, and less costly due to the fact that the acceleration measurement requires noninvasive sensing using generally much less expensive sensors rather than expensive pressure gages in the invasive mode. As a first step, using a small scale pipe network, we demonstrate results of an field experiment that serves as the proof of concept of this new technology which represents a prototype of the next generation of SCADA for water distribution systems.

7649-23, Session 5

Nondestructive monitoring of a pipe network using a MEMS-based wireless network

P. Chou, M. Shinozuka, Univ. of California, Irvine (United States)

Pressurized pipeline systems such as a water distribution network can be monitored nondestructively for the purpose of damage localization by measuring vibration on the pipe surface at various joints. The change in pipe vibration can be primarily attributed to the sudden change in the water pressure caused by a rupture in the network. One can locate the damage by analyzing time-synchronized data samples from two end joints and computing the local maxima of the water pressure gradient.

To enable large-scale deployment at an affordable cost, a MEMS-based wireless sensor network (WSN) is developed. It is composed of nodes, each of which consists of one or more sensor boards that can be daisy-chained underground to a shared wireless board for data uplink. A sensor board is equipped with MEMS accelerometers for measuring vibration on the exterior surface of the pipe without expensive, destructive modifications required of invasive monitoring techniques. MEMS accelerometers can be made much less expensive than piezoelectric ones, while the use of wireless links can save significant wiring cost for data communication and power. At the same time, wireless communication poses several challenges, including reliable communication over a relatively long distance, precise time synchronization over a relatively slow link, effective arbitration and allocation of bandwidth, and power management. We include multiple radio transceivers for failure redundancy and short-range transmission and control. Our system architecture is expandable and enables additional types of sensing devices to be incorporated, including camera modules, moisture sensors, and gas sensors for monitoring gravity pipes.

7649-24, Session 5

Self powered wireless acoustic emission sensor

D. Ozevin, V. F. Godinez, E. P. Lowenhar, M. F. Carlos, Physical Acoustics Corp. (United States); D. J. Inman, M. Lallart, Virginia Polytechnic Institute and State Univ. (United States); P. H. Ziehl, Univ. of South Carolina (United States); A. Nanni, F. Matta, Univ. of Miami (United States)

In this paper, the progress on the development of self powered wireless acoustic emission sensor under NIST Technology Innovation Program will be presented. Mistras Group Inc, Virginia Tech, University of South Carolina and University of Miami are developing a low power wireless Acoustic Emission (AE) sensor node integrated with an energy harvesting device and prognostic algorithms for steel and concrete bridges monitoring. This low power Acoustic Emission sensor node includes one AE and eight external parametric channels (e.g. strain, temperature). The sensor node communicates wirelessly with a base station module using the Zigbee wireless transmission standard. Power management circuits are included to control busy/idle modes based on external parametric input channels. Wind mill and piezoelectric based energy harvesting devices are being investigated. A set of ambient energy data, including wind, acceleration and strain, have been recorded from various bridge structures (i.e. suspension cable, pre-stressed I beam, multi-girder steel, concrete hollow box) in order to evaluate the energy harvesting potential of different structures. Based on the available energy, wind mill and piezoelectric based energy harvesting devices were investigated in order to harvest sufficient energy for the wireless AE sensor node. In this paper, laboratory scale demonstration of the wireless Acoustic Emission node integrated with the energy harvesting device will be presented. The power management strategies to reduce AE hit rate will be discussed. A brief overview of available ambient energy sources from bridge structures will be presented, and finally current status of energy harvesting device will be discussed.

7649-25, Session 5

Quantification of fatigue cracking in CT specimens with passive and active piezo-electric sensing

J. Yu, B. Zarate, J. Caicedo, V. Giurgiutiu, L. Yu, P. H. Ziehl, Univ. of South Carolina (United States); F. Matta, B. Metrovich, Univ. of Miami (United States)

Acoustic emission monitoring has been shown to be useful for the detection and evaluation of crack growth in steel bridges. The method has the advantage that the precise location of cracking does not need to be known for evaluation purposes. Rather, the sensors together with appropriate algorithms are capable of locating and quantifying active crack activity. Due to the age of the transportation infrastructure this method of health monitoring is receiving renewed attention. One of the challenges is the transmission of the acoustic emission data through wireless means and related to this is the need for robust algorithms from sparse data sets. Challenges also exist in relating the sensed data to the remaining strength or fatigue life of a component or system.

In the work described a model updating approach is developed to address these challenges.

One of the difficulties with passive monitoring is that active crack growth is required to excite the sensors. Active sensing (piezoelectric wafer active sensing) provides an alternate means of detection and importantly may also provide a method to detect the extent of crack growth after the event. Active sensing has similar challenges to passive sensing in relation to data transmission and the development of robust algorithms.

The application of both passive and active piezo-electric based sensing is described for cyclically loaded steel compact tension test specimens. The specimens are representative of steel bridge construction. The model updating approach is also described for assessment of remaining fatigue life.

7649-26, Session 5

Method and experiments for correction of strain-transfer errors in long gauge optical fiber sensors

X. Zhang, C. Sun, X. Feng, T. Taylor, F. Ansari, Univ. of Illinois at Chicago (United States)

Fiber optic white-light interferometer has been successfully employed in deformation measurements with micron-sized precision and high repeatability. In this study we developed a test program for the analysis and development of a methodology for correcting the errors associated in transfer of strain from the structural elements to the optical fiber. The experimental program considers various loading patterns and strain distributions along the length of the beam. Based on the theoretical model for the strain transfer process between the host material and fiber a model has been developed for quantitative analysis of strain transfer errors. Results from the study presented here also provide means for practical installation of long gauge sensors in structural elements.

7649-27, Session 5

Improved sensing schemes with Brillouin optical time domain refelectometry

C. Sun, X. Feng, X. Zhang, F. Ansari, Univ. of Illinois at Chicago (United States)

Brillouin optical time domain refelectometry (BOTDR) has been attracting intense interest for distributed strain monitoring in large scale structures, such as oil pipe lines, and geotechnical applications. In this technique, the spontaneous Brillouin scattering (SBS) signal along the length of an optical fiber cable can be measured by coupling a pulsed pump signal into the fiber and detecting the change in the Brillouin frequency shift caused by strain or temperature added to the optical fiber. The strain coefficient can reach to 505MHz/% and its counterpart temperature coefficient is around 0.95MHz/degrees C. A one meter spatial resolution can be achieved by controlling the pulsed pump signal width to 10ns. Most of the practical applications are the trade-off between the sensitivity and the spatial resolution. Higher spatial resolution requires a more narrowly pulsed pump signal, which narrows the frequency spectrum and decreases the signal to noise ratio. Practical implementation of the BOTDR systems in civil structures require achieving high signal to noise ratios. In order to get a good balance between these two factors, we designed several schemes to test the possibility to improve the spatial resolution near the edge of the strain and temperature changes, even if sacrifices the sensitivity somehow.

7649-28, Session 5

A method and theory for temperature compensation in long gauge fiber

X. Feng, C. Sun, X. Zhang, F. Ansari, Univ. of Illinois at Chicago (United States)

Long gauge fiber optic sensors provide for high precision measurements. However, the temperature sensitivity of the sensor limits its usefulness in practical applications. In this study, we propose a novel method to compensate the temperature effect on long gauge fiber optic sensors. The sensing scheme uses two coupled long gauge sensors: one is attached on the structure to sense deformation while another is loose to sense environmental temperature variation. In order to thoroughly eliminate the temperature effect, a strain transfer model of attached sensor is analytically derived. Then a theoretical formula is proposed to compensate the temperature effect by using of the measured results of the attached sensor as well as the loose sensor. By comparing with the previous approaches, the proposed method considers the strain transfer from host component to fiber core, which significantly improve the accuracy of the temperature compensation for long gauge sensors. The experimental results show that the deformation created by external load can be exactly measured when the environmental temperature is changed.

7649-29, Session 5

Damage simulation and verification for structural health monitoring on carbon epoxy composite structures

S. B. Shen, H. Chung, T. Chang, X. P. Qing, S. J. Beard, Acellent Technologies, Inc. (United States)

The fatigue life and damage tolerance of composite structures are strongly affected by impact damages, mainly in the form of delamination. Different approaches of structural health monitoring (SHM) have been developed for composite structures. However, all the SHM techniques need to be verified without damaging the structures. A specific verification procedure is developed by using damage simulators with unique materials and geometry design. It is the intent of this paper to verify the correlation of real damage and damage simulation multilayer damage simulator. The standard process for multilayer damage simulators shows agreement between the results from impact damages and ones from damage simulators. The verification comprises: install the health monitoring system on the structure to be detected and run the system to get the baseline data; attach at least one damage simulator on the structure to be detected; run the health monitoring system to get the test data; compare the test data with the baseline data to get the damage information (including damage location and damage size,) to verify the damage detection capability and accuracy of the health monitoring system used. The SHM verification is performed on a piezoelectric sensor system containing SMART Layer, ScanGenie and the software of SmartComposite.

7649-83, Session 5

Versatile onboard traffic-embedded roaming sensors

M. L. Wang, Northeastern Univ. (United States)

One of the principal means of insuring the robustness and longevity of infrastructure is to strategically deploy smart sensors in them. Therefore, the objective is to develop novel, durable, smart sensors that are especially applicable to urban infrastructure and the facilities to validate their reliability and long-term functionality. In some cases, this implies the development of new sensing elements themselves, while in other cases involves innovative packaging and use of existing sensor technologies. In either case, a parallel focus will be

the integration and networking of these smart sensing elements for reliable data acquisition, transmission, and fusion, within a decision-making framework targeting efficient management and maintenance of infrastructure systems.

VOTERS (“versatile onboard traffic-embedded roaming sensors”) aims to provide a continuous stream of accurate, up-to-date information about the state of roadways and bridge decks gathered by sensor systems mounted on vehicles of opportunity, while also eliminating the hazardous, congestion-prone work zones that are often set up to gather this critical data. Research will focus on development of a cost-effective, lightweight package of advanced radar, acoustic, optical, and GPS sensors that will be integrated into one VOTERS system which can be mounted on regular cars and trucks (vehicles of opportunity) to gather information as navigate through daily traffic. The VOTERS data will be available through a centralized geospatial database coupled with GIS applications for data access. The project involves significant research challenges - in particular the development of inexpensive sensors that collect data at regular driving speeds without contacting the road, while guaranteeing accurate geo-referencing of all data streams. The VOTERS project is funded under the TIP program of the NIST and will run for five years at a total cost of $18.4 million, including cost-sharing by the project participants. The VOTERS include about 45 faculty, research scientists, staff, and graduate students from three universities as well as research engineers from two industrial joint venture partners.

7649-62, Poster Session

The design of delay pulse circuit for ultrasonic phased array system

H. Wang, Harbin Institute of Technology (China)

Simple ultrasound systems use a single large piezoelectric transducer to generate and receive ultrasound. However, state of the art systems use phased array technology similar to that used in contemporary radar and sonar. These systems use transducer arrays comprising a multitude of small transducer elements. Ultrasonic phased array techniques have been used in modem medicine and industry for NDT.

This paper presents architecture of delay pulse circuit for both transmit and receive beamformer, which is designed for 8 elements. Instead of using a single high-speed clock and analog or digital delay lines to meet the resolution requirements, the design employs the phase shifting with phase locked loop (PLL) which is built in FPGA chips.

The design of 8-channel delay pulse circuit to drive ultrasonic array transducers is proposed. The hardware is built with FPGA. The specified time resolution of 1ns has been met. And the results of test of the design are compared with several programmable delay chips and have demonstrated that high delay with 1-ns resolution can be produced using the presented design.

An architecture of receive beamforming for ultrasonic phased array system is proposed. The generation of non-uniform sampling clocks is considered. For convenience, other blocks such as A/D converters, FIFO registers and Adder are not discussed because they are common to any phased array system. The results of the test of the design are compared with two programmable delay chips and have demonstrated that high delay with 1-ns resolution can be produced using the presented design.

7649-64, Poster Session

Global mechanical behavior of Sutong Bridge under static loads

Y. Li, Q. Zhang, Tongji Univ. (China)

The present work describes the global mechanical behaviors of kilometer-level cable-stayed bridge by using field static load tests on Sutong Bridge. A total of 37 loading cases with 64 test trucks which a vehicle’s axle weight is 300kN were conducted on 10 key sections to investigate the bridge behavior. The real working condition include strength, stiffness and nonlinearity of the bridge are studied. A full-scale structural model and local-scale member model connected by submodel method was established. A very good agreement is achieved between the experimental tests and numerical simulations, which indicate that the mechanical behaviors of the kilometer-lever cable-stayed bridge can be investigated exactly using existing nonlinear theories of long span bridges. The results show that the bridge under the planned load test conditions has good overall static properties and works in the elastic stage. The incremental deflections and stresses as well as cable force are observed to be linearly proportional to incremental load. Because of the shear lag effect, influence of transversal slope and effect of local stress, the longitudinal flexural stress discrepancies at the top and bottom flanges, U-ribs of steel box girder subjected to symmetrical loads were observed to be significant. The stresses of the flanges and U-ribs remain generally the largest value located at the junction of stiffeners and flanges. And the alternating tension-compression stresses in the top U-rib were observed, which demonstrate that the U-ribs are of critical importance in structure health monitoring and fatigue assessment because of its large range of stress variation.

7649-65, Poster Session

Non-linear material characterisation using the noncollinear method

A. J. Croxford, P. D. Wilcox, B. W. Drinkwater, Univ. of Bristol (United Kingdom); P. B. Nagy, Univ. of Cincinnati (United States)

Conventional ultrasonic NDT techniques are limited in their ability to detect small defects by the diffraction limit, that is there is much reduced sensitivity to defects smaller than the wavelength of the interrogating ultrasonic wave. While not a major issue for most inspection, this problem becomes particularly significant for the detection of fatigue damage prior to crack formation. In this regime conventional NDT has proven to be inadequate. For this reason significant effort has been expended on the development of non-linear techniques. These techniques rely on deviations of the material from linear stress strain behaviour which create harmonics in the resulting frequency response. Evidence suggests that changes to a materials condition, such as fatigue damage, change this non-linear response. This paper presents a non-linear inspection method using a non-collinear interaction. This technique has several advantages over other harmonic approaches in that there is spatial separation, modal separation and frequency separation of the non-linear signal. This allows the origin of the non-linear signal and underlying noise levels to be well defined. The capability of the technique is demonstrated using plastically strained material and samples subjected to low cycle fatigue.

7649-66, Poster Session

A damage detection approach based on multi-scale numerical model for composite structures with truss core

H. Fang, China Academy of Engineering Physics (China) and Xi’an Jiaotong Univ. (China)

This paper presents a damage detection approach for composite structures with truss core basing on multi-scale numerical modeling.

In the composite structures with truss core, local material deterioration at members of truss core is able to account for the major effect of the damage on structural strength. In a general way, the existing damage detection approaches for composite structures carry out analyses based on single-model, in which details of local deterioration on the scale of the material point cannot be represented. In this paper, local material deterioration is modeled based on the theory of continuum damage mechanics and then shifted into the global model at the structural level for global analysis. The models’ shift is implemented by the transition using a multi-point constraint equation. On the basis of the multi-scale modeling, the inverse problem to detect damage utilizing dynamic information is proposed, in which the local material

deterioration at multiple members can be accurately estimated. Prediction of the remaining service life of the structure is generally associated with the fields of material deterioration analysis, which is not addressed in this paper.

A multi-scale numerical model, which represents global structure, critical components and possible material deterioration in local details, is particularly advantageous for evaluating damage in composite structure with truss core. As a validation, the proposed method is applied to detect damage of a composite panel with truss core. In this paper, all computations are implemented by Matlab.

7649-68, Poster Session

Damage propagation monitoring of composite blade under fatigue loading

W. Zhou, H. Li, Y. Wang, Harbin Institute of Technology (China)

The blades of a wind turbine rotor are generally regarded as the most critical component of the wind turbine system. Especially, wind turbine blades are made of fiberglass material to be cost effective, but they can be damaged by moisture absorption, fatigue, wind gusts or lightening strikes. In addition, normal aerodynamic loads and loads due to changing gravity moments cause fatigue damage of the blades. Therefore it is important to detect the damage before the blade fails catastrophically which could destroy the entire wind turbine. Structural health monitoring (SHM) is now regarded as an essential tool and part of any MW class of wind turbine to evaluate the status of the composite blades. In this paper, a 2.1m long glass fibre reinforced plastic composite wind turbine blade was carried out under the fatigue loading to simulate the damage procedure, i.e. the producing and propagation of damage or crack. Piezoelectric transformers bonded to the blade and fractal theory-based damage detection method are used to monitor and evaluate the damage propagation during the test. Results showed above work enables the evolution of the damage to be monitored.

7649-69, Poster Session

The next generation magnetovision system for SMART applications

D. Lewandowski, J. Kaleta, P. Wiewiórski, Wroclaw Univ. of Technology (Poland)

The original method, measurement devices and software tool for examination of magneto-mechanical phenomena in wide range of SMART applications is proposed. In many Hi-End market constructions it is necessary to carry out examinations of mechanical and magnetic properties simultaneously. Technological processes of fabrication modern materials (for example cutting, premagnetisation and prestress) and advanced concept of using SMART structures involves the design of next generation system for optimization of electric and magnetic field distribution. The original fast and higher than million point static resolution scanner with mulitsensor probes has been constructed to measure full components of the magnetic field intensity vector H, and visualize them into end user acceptable variant. The scanner has also capability to acquire electric potentials on surface to work with magneto-piezo devices. Advanced electronic subsystems have been applied for processing of results in The Magscaner Vison System and the corresponding software - Maglab has been also evaluated. The Dipole Contour Method (DCM) is provided for modeling different state between magnetic and electric coupled materials and to visually explain the information of the experimental data. Dedicated software collaborating with industrial parametric systems CAD. Measurement technique consists of acquiring a cloud of points belonging to equally distant planes, similarly as in tomography, 3D visualisation in CAD under mulitlayer IGES standard. The actually carried verification of abilities of 3D digitizer will enable inspection of SMART actuators with the cylindrical form, pellets with miniature sizes designed for oscillations dumpers in various construction, for example in vehicle industry.

7649-70, Poster Session

Characterization of pitting corrosion on small diameter ductile iron pipe using thermography

Z. Liu, M. Genest, National Research Council Canada (Canada)

Ductile iron (DI) pipe became the principal pipe material used for many municipalities since the late 1960s. The condition of a DI pipe is determined by not only its age, but also a number of other factors, such as electrochemical and physical properties of surrounding soils, which have an impact on the pitting corrosion of the DI pipe. However, the mechanism of pit growth has not been fully explored and understood. This requires the development of a statistical model that can relate current condition of pipes and corrosion rates with existing soil properties. The corrosion rate is defined as the ratio of pipe material loss over time span. In order to establish a relationship between the soil environment and pipe corrosion rate, the pitting corrosion needs to be quantified.

One approach to accurately map pitting corrosion is with a high-resolution laser scanner. However, this process is time consuming and requires the removal of the pipe segment and sandblasting of its surface. Thermography is considered for the field testing. In this study, we investigated the potential of quantifying pitting corrosion with thermography technique. A cleaned pipe was inspected with the thermography technique. The algorithm to characterize the pitting corrosion in terms of material loss is presented in this paper.

7649-71, Poster Session

Experimental investigation on mechanical behavior of filament-wound CFRP tubes

L. Zhang, Northeast Forestry Univ. (China); H. Li, Harbin Institute of Technology (China); J. Ou, Dalian Univ. of Technology (China)

Firstly, two types of CFRP tubes are designed using the filament-wound forming technology. These tubes are winded by carbon fibers with a filament winding pattern of [(900/00)2]S. The compression and tensile test are also carried out to investigate the stress-strain relationship, ultimate strength and macroscopic failure mode of the former CFRP tube. The results demonstrate that the former CFRP tube has a much larger ultimate tensile stress and strain than compressive stress and strain. However, the elastic modules of CFRP tubes under tension and compression are similar and the failure mode of these CFRP tubes is brittle under compression and tension. Secondly, the stress and strain analysis method of filament-wound CFRP tube is investigated according to anisotropic elasticity theory and lamination theory of composite material. Then, the strength of carbon-fiber-reinforced plastic tubes is obtained. In addition, the comparison of theoretical analysis results and experimental results shows that the theoretical analysis results are reliable.

7649-73, Poster Session

Measurement of surface resistivity/ conductivity of anodized aluminium alloy by optical interferometry techniques

K. J. Habib, Kuwait Institute for Scientific Research (Kuwait)

Optical interferometry techniques can be use for the first time to measure the surface resistivity/conductivity of an anodized ,oxide,layer of an aluminium alloy without any physical contact. This can be achieved by applying an electrical potential across the alloy and measuring the electronic current flow across the alloy as a result of the electrical potential. In the mean time, optical iterferometry techniques such as holographic interferometry can be used in situ to measure the orthogonal surface displacement of the anodized layer of the aluminium sample, as a result of the applied electrical potential. In addition, a

mathematical model can be derived in order to correlate the ratio of the electrical potential to the electronic current flow (electrical potential/ electronic Current flow=resistance) and to the surface (orthogonal) displacement of the sample. In other words, a proportionality constant (surface resistivity or conductivity=1/ surface resistivity) between the measured electrical resistance and the surface displacement (by the optical interferometry techniques) can be obtained. Consequently the surface resistivity/ and conductivity of the anodized layer of the aluminium sample can be determined, without any physical contact.

7649-75, Poster Session

Dynamic behaviour analysis for catwalks without wind-resistant cable of long-span suspension bridge

S. Li, Zhengzhou Univ. (China); J. Ou, Harbin Institute of Technology (China)

On the basis of methods of theoretical derivation and finite element ANSYS modelling, the dynamic behaviour of catwalks without wind-resistant cable of long-span suspension brdige was studied. The vibration frequencies of the first order vertical and side directions, and the first order torsional frequency are derived in theory. The influence of the related parameters which include the pylons, the ratio of rise to span, the transverse overbridges, the material performance and the coupling cables etc on dynamic behabiour of catwalks was researched using theoretical calculation and model analysis of prestressing cable structures of finite element ANSYS. Results show that the vibration frequencies of the first order symmetry, antisymmetry side directions and antisymmetry vetical direction of the catwalks are independent of the tension of load bearing cables and quality of per-span-length; the influence of pylons on natural frequency of the catwalks without wind-resistant cable is little; the vibration frequencies of the catwalks submit the reduced trend with the increace of the ratio of rise to span; The influences of the positions and population of the transverse overbridges are trivial on low order frequencies and large on the high order frequecies; the parallel cables make almost no difference on the every frequencies and the across cables have no effect on low frequency and have to a certainty advance on the torsional frequencies; the natural frequencies of the catwalks with the bearing ropes made in CFRP and steel are nearly identical,but the catwalks with the bearing ropes made in CFRP reduce the require on the construction machinery such as winding machine.

7649-30, Session 6

Fabrication and characterization of high frequency phased arrays for NDE imaging

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PMN-PT single crystal 1-3 composite high frequency phased arrays with center frequency of 10 MHz and 35 MHz were fabricated and characterized for SiC NDE imaging applications. The 10 MHz 64-element array was fabricated using the conventional dice-and-fill process. The electromechanical coupling coefficient of the fabricated 1-3 composite is about 0.79. The prototyped 64-element array was characterized by measuring the capacitance and impulse response of each element. The measured impulse-response showed that broad bandwidth (~ 75%) was obtained, which is similar to that of commercial 10 MHz arrays, but with the sensitivity doubled. The 35 MHz 64-element array was successfully built, for the first time, for ultrasound NDE application. The 1-3 composite was fabricated using the recently developed PC-MUT technology, which utilized deep reactive ion etching process to for fine pitch piezo structures. The electromechanical coupling coefficient of the fabricated 35 MHz 1-3 composite is about 0.75. The prototyped 35 MHz 64-element phased array was characterized by measuring the capacitance and impulse response of each element. The Measured element bandwidth was > 90%, and the sensitivity remained to be high (echo amplitude > 500 mV from the impulse response with 0 gain). NDE imaging experiments using these phased arrays is being investigated and more results will be reported in the full paper. These high frequency phased arrays are promising for ceramic NDE imaging.

7649-32, Session 6

Ultrasonic inspection technique for NDE of fibre composite materials

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The constant growth of air traffic leads to increasing demands for the aircraft industry to manufacture airplanes more economically and to ensure a higher level of efficiency, ecology and safety. During the last years important improvements for fuselage structures have been achieved by application of new construction principles, employment of sophisticated and/or alternative materials, and by improved manufacturing processes. In particular the intensified application of fibre-reinforced plastics components is in the focus of current discussions and research.

The main goal of an ongoing national project is to improve the existing ultrasonic test technology in such a way that it is optimally suited for the examination of CFRP multilayer structures. The B-Scan and C-Scan results are then used for the visualization of individual layers and the complete layer set-up.

First results of the project revealed that with carefully selected transducers and frequencies it is possible to detect defects and irregularities in the layer structure like delaminations, fibre cracking, ondulations, missing layers etc. and even to visualize the fibre orientations in the individual layers.

7649-33, Session 6

Early detection of buckling in structural members using stress wave technique

M. J. Sundaresan, K. Asamene, B. Ali, North Carolina A&T State Univ. (United States)

Buckling is an important failure mode in structures composed of slender members and those with hollow cross sections. In the initial stages of this instability, deformation is may be entirely elastic and hence, if the onset of buckling is detected in a timely manner, there is a possibility of averting complete failure by taking appropriate measures. In other situations, local damage in the in the form of disbond between the skin and the stiffener can lead to local buckling. Such local buckling may an effective indicator of the internal damage present in such structures and hence the detection of such disbonds is of considerable interest in structural health monitoring.

Earlier studies indicated that vibration characteristics can provide a simple means of detecting the onset of buckling in bar like structures. Significant changes in the mode shapes as well as resonance frequencies resulted even in the very initial stages of buckling deformation. In addition, experimental results on wind turbine blades indicated that wave propagation may be a useful tool in detecting instability in hollow sections.

The present paper compares the effectiveness of vibration based approach with the stress wave propagation approach for the early detection of elastic buckling in bars and plates. Finite element technique was used for evaluating the effectiveness of the two approaches. Tone bursts were used to excite and propagate stress waves through the region of buckling deformation in these structural elements. The changes in the characteristics of the received signal in terms of amplitude and dispersion were used as indicators of the onset of buckling deformation. From such simulations, optimal frequency of stress waves to be employed for different configurations is determined. The results are compared with available experimental results.

Conf. 7649: Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security IV

7649-34, Session 6

Service induced damage in composite laminates: non destructive assessment, quantification and modeling

D. G. Aggelis, N. Barkoula, T. E. Matikas, A. S. Paipetis, Univ. of Ioannina (Greece)

Acoustic emission is a powerful technique for identifying, monitoring the evolution of service induced degradation in structural components and localising damage. The present study is dedicated to the investigation of model composite systems in order to identify, locate and quantify service induced damage. These systems are cross ply translucent glass fibre reinforced composite materials. In cross ply composites, service induced primary damage is manifested in the form of matrix cracking of the off-axis laminates. The optical translucence allows for the direct observation of the cracks which appear as lines transverse to the loading direction.

For the purposes of this study, the translucent cross ply composite were subjected to monotonic loading, step loading and fatigue loading with the concurrent recording of the acoustic activity. At specific intervals of the loading process the propagation characteristics of low frequency ultrasonic waves were also recorded using the acoustic emission sensors in a pulser-receiver setup. The acoustic emission activity has been successfully correlated to the various damage modes that evolve during the loading of the cross ply laminates, and could accurately localise the transverse cracks along the length of the specimen, and therefore provide a real time estimate of the crack density as was optically verified. Constitutive analytical modelling was subsequently employed to assess the stiffness degradation of cross ply laminates in relation to the crack density. The frequency dependence dispersion of the acoustic waves was also correlated to the damage induced degradation of the material.

7649-35, Session 6

Acoustic emission characterization of steel fiber reinforced concrete during bending

D. G. Aggelis, D. V. Soulioti, N. Sapouridis, N. Barkoula, A. S. Paipetis, T. E. Matikas, Univ. of Ioannina (Greece)

The acoustic emission (AE) behaviour of steel fiber reinforced concrete is studied in this paper. The experiments were conducted in four-point bending with concurrent monitoring of AE signals. The sensors used, were of broadband response in order to capture a wide range of fracturing phenomena. The results indicate that AE parameters undergo significant changes much earlier than the final fracture of the specimens, even if the AE hit rate seems approximately constant. Specifically, the Ib-value which takes into account the amplitude distribution of the recent AE hits decreases when the load reaches about 60-70 % of its maximum value. Additionally, the average frequency of the signals decreases abruptly when a fracture incident occurs, indicating that matrix cracking events produce higher frequencies than fiber pull-out events. Different types of steel fibers are used in order to compare their contribution in the mechanical behaviour of concrete. It is concluded that proper study of AE parameters enables the characterization of structural health of large structures in cases where remote monitoring is applied.

7649-36, Session 6

Using 2-D arrays for sensing multimodal Lamb waves

T. Stepinski, M. Engholm, Uppsala Univ. (Sweden)

Monitoring structural integrity of large planar structures that aims at detecting and localizing impact or damage at any point of the structure requires normally a relatively dense network of uniformly distributed ultrasonic sensors. A 2-D ultrasonic phased array with all azimuth angle coverage would be extremely useful for the structural health monitoring (SHM) of such structures. Estimating direction of arriving (DOA) waves is one of the fundamental issues when using arrays in SHM applications. Although a number of DOA estimation techniques have been developed, none of them can efficiently cope with dispersive and multimodal Lamb waves (LWs).

In the paper we propose an adaptive high-resolution spectral estimation technique capable of handling broadband LWs sensed by 2-D arrays, the modified Capon method. Performance of the proposed technique is evaluated using simulated multiple-mode LWs, and then verified using experimental data. The experimental data was obtained using a prototype square 8x8 array sensing dispersive waves propagating in thin plates. The array was provided with an analog multiplexer that enabled recording signals received by the individual elements using a digital oscilloscope. The array was receiving ultrasonic pulses sent by a broadband piezoelectric transmitter and reflected from artificial defects. The results presented in the paper demonstrate both DOA estimation and source separation ability of the proposed technique. The technique that can be used for various array topologies appears to be a very flexible and powerful method for Lamb wave characterization.

7649-63, Session 6

Evaluation of bridge cable corrosion using acoustic emission technique

D. Li, Dalian Univ. of Technology (China)

Owing to the nature of the stress, corrosion of bridge cable may result in catastrophic failure of the structure. However, using electrochemical techniques isn't fully efficient for the detection and control on line of the corrosion phenomenon. A non-destructive testing method based on acoustic emission technique monitoring bridge cable corrosion was explored. The steel strands were placed at room temperature in 5% NaCl solution. Acoustic emission characteristic parameters were recorded in the whole corrosion experiment process. Based on the plot of cumulated acoustic activity, the bridge cables corrosion included three stages. It can be clearly seen that different stages have different acoustic emission signal characteristics. The acoustic emission characteristic parameters would be increased with cables corrosion development. Finally, the bridge cables corrosion experiment with different stress state and different corrosion environment was performed. The results shows that stress magnitude and solution concentration only affects the bridge cable failure time, however, the acoustic emission characteristic parameters value has changed a little. It was verified that acoustic emission technique can be used to detect the bridge cable early corrosion, investigating corrosion developing trend, and in monitoring and evaluating corrosion damages.

7649-37, Session 7

Lamb wave excitation and detection with smart fasteners for structural health monitoring

H. Yoon, Tennessee Technological Univ. (United States)

The capability of smart fasteners to excite and detect Lamb waves in the clamped structure for structural health monitoring is investigated. The smart fasteners have an embedded piezoceramic stack transducer that can apply transverse force to the clamped structure or detect transverse vibration of the structure. In this study, a mathematical model of the Lamb wave generation and detection mechanisms for the smart fasteners is derived using the potential function method. Using the space domain Fourier transform, the model is transformed into the wavenumber domain where the boundary conditions are applied to get the solution. The obtained solution is converted back into the physical space with the inverse Fourier transform. Finally, closed-form solutions for the surface strain and displacement are obtained using the residue theorem in the complex plane. Using the analytic solutions,

mode tuning capabilities of the smart fasteners are studied. The results show that the tuning of certain modes at certain frequencies can be achieved.

7649-38, Session 7

Active data selection for adaptive online structural damage estimation

D. Chakraborty, N. V. Kovvali, A. Papandreou-Suppappola, A. Chattopadhyay, Arizona State Univ. (United States)

Adaptive learning techniques are state-of-the-art statistical methods that have recently been successfully used in structural health monitoring applications for baseline-free damage classification.

The adaptive learning methodology is based on a state-space formulation, where the evolution of damage state is described by a Markov relationship that accounts for variability in the environment or the structure itself. The observations in the formulation are composed of clusters identified adaptively using Dirichlet process (DP) mixture models of time-frequency features that are extracted from Lamb wave responses. Once the formulation is established, Bayesian filtering can be used to estimate the progressive damage. However, this approach does not exploit the fact that the observations used for the estimation can be optimally chosen to yield maximum damage information.

In this paper, we propose to use an active data selection process to intelligently choose the features or data that will maximize our damage estimation performance. In particular, we will incorporate the active learning approach into the adaptive progressive damage estimation so that it can be used to actively select the measurements which are most informative for the purpose of damage estimation, resulting in a more efficient and effective damage estimation framework. This will have the advantage of resulting in a fully automatic and unsupervised system, facilitating baseline-free and online implementation. In order to demonstrate the proposed method, we will present results for the online estimation of fatigue crack length in aluminum alloys.

7649-39, Session 7

Inverse problem for material non destructive analysis by ultrasound

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Due to the exact defect localization, sensitivity to inner flaw detection and identification benefit, ultrasonic testing is widely used in the inspection of many industrial components as austenitic steel or composite samples. Ultrasonic data are difficult to interpret since they require the analysis of a continuous signal for each point of the material under consideration. Due to the inherent inhomogeneous and anisotropy nature of these materials, ultrasonic waves undergo high acoustic attenuation and scattering effect, making data interpretation highly complex. Echoes backscattered from the front and back surface of specimen, combined with other backscattered flaws or microstructures echoes, are often overlapped, making the identification of flaws difficult. Thus, the visibility of flaw echoes is usually corrupted by electrical, pulse, ringing and structure noises and spurious signals. Presence of the additive structural noise from grain boundaries and other microstructures limit detection of small cracks, flaws or other defects. Consequently, a well-adapted kind of signal analysis is required to interpret the ultrasonic inspection signals for ensuring the reality of defect echo-signals. Calssical de-noising methods are useful, if this noise is a zero-mean Gaussian white noise, but have some limitations affecting the reliability of testing results and the accuracy of location, quantitative analysis and evaluation. In the proposed de-noising procedure the noise features were extracted by an energetic smoothing algorithm by which the random nature of the noise in the spatial domain is bypassed. This energetic characterization of the structure noise and the defect to be detected has given an improved filtering process with accurate signal reconstruction and enhanced detection. However if anisotropic noise is related to local variations in texture or shapes of macro etches, the relationship of this ultrasonic property to microstructure is not well understood, and no careful theory has been presented to quantitatively describe these relationships.

The following experiments obtained from a structural noise of a steel plate, will give significant insights into the relationship of backscattered noise and microstructure which will ensue to understand the microstructure dimension scales.

7649-40, Session 7

Ultrasonic NDE for the characterization of metallic structures and natural materials

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In this study an inverse procedure based on guided wave propagation is proposed for the characterization of the elastic constants of aluminum and bamboo. The procedure consists of an optimization problem in which the discrepancy between the dispersion curves obtained through a semi analytical finite element (SAFE) formulation and experimental dispersion curves is minimized. Experimental data were obtained by adopting a hybrid broadband laser/PZT setup. The optimization scheme proposed is based on an improved version of the simplex search method where an initial guess of the material parameters in the SAFE formulation. The values of these parameters are iteratively updated until the discrepancy between the SAFE-based group velocity dispersion curves and the numerical or experimental curves is minimized. The validity of the SAFE method coupled to the inverse procedure scheme is tested to characterize the elastic material properties of an aluminum plate and a structural bamboo culm.

7649-41, Session 7

Instrumentation for EMAT based non-destructive testing

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Abstract:

Electromagnetic acoustic transducers have been of interest to the NDT community for many years due to its numerous advantages over the contact transducers. An electromagnetic acoustic transducer generates ultrasonic energy into an object by applying a static magnetic field to object using a magnet and inducing a radio frequency (RF) eddy currents into the object using the RF coil. The RF pulses interact with the magnetic field to produce Lorentz force, which in turn produces ultrasonic waves in the object at the radio frequency. The strength of the generated force mainly depends on the static magnetic field, RF coil current and the proximity of the probe to the test specimen. National Physical Laboratory, India is actively involved in the improved design and development of EMAT and its associated instrumentation since 2008. In this article the critical design considerations of EMAT for its improved efficiency is described. A novel software and hardware based technique for the high resolution (1 nS) time of flight (TOF) is also explained in this article.

7649-42, Session 8

Transient infrared thermography for damage evaluation in foam core aerospace sandwich composites

S. S. Pawar, D. A. Hackney, K. J. Peters, North Carolina State Univ. (United States)

We present transient infrared thermography imaging of foam core aerospace sandwich composites for the identification of common failure modes including facesheet debonding and shear cracking in the Rohacell foam core. We demonstrate that adaptive image processing

of the obtained images yields enhanced damage identification capabilities. The imaging results are classified based on known damage parameters induced by controlled low-velocity impact testing of the sandwich laminates. The particular damage states are also verified independently through embedded fiber Bragg grating sensors at the foam core/facesheet interface. Thermal loading of the sensors throughout the infrared thermography loading cycle provides additional data to be input into the adaptive image processing algorithm. The results of this combined infrared thermography and internal sensing are compared to classical, pure transient infrared thermography and lock-in infrared thermography techniques. Comparison between the results of the sandwich laminates and conventional graphite-fiber epoxy laminates are also presented.

7649-43, Session 8

Application of line scanning thermography for the detection of interlaminar disbonds in sandwich composite structures

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An innovative Line Scanning Thermography (LST) inspection method is being developed as part of a Structural Damage Assessment System to access the health of in-service composite structures. The system utilizes a line heat source to thermally excite the surface inspected and an infrared detector to record the transient surface temperature variation and to detect regions of increased heat resistance associated to interlaminar disbonds, cracks and other imperfections found in composites structures. For this study, a portable inspection system, referred to as THELIS (Thermography Line Inspection System) was developed and used.

In this work, our efforts towards the applications of LST for the analysis of carbon fiber sandwich composites will be discussed. The LST technique provides a quick and efficient methodology to scan wide areas rapidly. The scanning protocols developed for the detection of sub-surface disbonds (delamination) in composite sandwich parts will be presented. The results presented correspond to both scans of test coupons with manufactured defects, and scans of in-service parts. In order to identify the type of defects than can easily observed with noncontact thermography inspection, this study shows a comparison of the thermal images acquired using LST and ultrasonic c-scans.

In the samples and test coupons studied, characterized by a top layer thickness of 3/8”, it was observed that the LST technique is capable of detecting delaminations among the top composite layer and the core; and that the inspection can be performed at a rate of 0.5in/s, which produces a coverage area of 1 ft2 in 29s.

7649-44, Session 8

Detection of surface breaking cracks using thermographic and non-contact ultrasonic methods

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A combined ultrasound and thermography defect detection system using a raster scanned Q-switched laser as a source of heat and ultrasound has been developed for identifying surface breaking defects. Heat is generated on a sample surface by a laser source and the resultant thermal image is examined by a thermal imaging camera. This can be done using a cw or a pulsed laser, but for ultrasonic generation a pulsed laser beam is required. When a defect is present, the flow of heat in the sample is disturbed and a change in shape of the thermal spot on the sample’s surface can be detected. The pulsed laser beam generates simultaneously an ultrasonic wave that can be detected by a suitable transducer, which in this case is an electromagnetic acoustic transducer (EMAT). The presence of a defect changes both the amplitude and frequency content of the received wave. Three dimensional finite element modelling of the interaction between Lamb waves and defects have been studied and compared with experimental data, in order to optimise source and detector positions around a defect. The approach can detect surface crack defects via the ultrasonic and thermography method in one measurement.

7649-45, Session 8

Repair integrity monitoring of composite aerostructures using thermographic imaging

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Bonded repair offers significant advantages over mechanically fastened repair schemes as it eliminates local stress concentrations and seals the interface between the mother structure and the patch. However, it is particularly difficult to assess the efficiency of the bonded repair as well as its performance during service loads. Thermoghraphy is a particularly attractive technique for the particular application as it is a non-contact, wide field non destructive method. Phase thermography is also offering the advantage of depth discrimination in layered structures such as in typical patch repairs particularly in the case where composites are used. Lock-in thermography offers the additional advantage of on line monitoring of the loaded structure and subsequently the real time evolution of any progressive debonding which may lead to critical failure of the patched repair.

This study focuses on the on line repair integrity monitoring with respect to bonding performance (degree of edge debonding-critical damage and/or damage/crack propagation and debonding within the repaired structure underneath the patch-critical damage) using advanced thermographic techniques such as pulsed phase and lock-in Thermography. Model repaired systems were manufactured and subjected to thermal and or mechanical loading in order to assess the efficiency of the technique, particularly for on line monitoring. The obtained results are compared with typical C-scans and a comparative assessment of the accuracy of the two methods is presented.

7649-46, Session 9

A tunable impulse ultra-wide-band sensor for civil infrastructure sensing applications

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Impulse ultra-wideband (UWB) sensor is attractive for high-resolution sensing applications, particularly for civil infrastructure evaluation such as assessment of pavement, bridge, tunnels and buildings, and surveillance and monitoring of hidden objects and activities. Impulse radars have been used for assessing pavements and bridges. However, these radars are typically operated with a fixed transmitting pulse, hence limiting their operating ability such as detection and characterization of only certain targets, at certain penetration depths and with certain resolutions. For certain practical applications, such as those requiring fine resolution or large range, better capability sensors are needed.

We present a new impulse UWB sensor and demonstrate its enhanced sensing capability. The sensor, consisting of transmitter, receiver and antennas integrated together in a single package, is capable of transmitting impulse signals varying from 450 to 1170 ps and detecting signals up to 5.5 GHz. It has a range resolution of about 1 inch. The system can vary the transmitting pulse duration, thus effectively simulating multiple UWB systems working together consecutively. This unique pulse-variation capability not only reduces the sensor cost, but also provides flexibility in the operation and application of the sensor and enhances its ability in detecting and classifying targets in different environments. The varying pulses can also be exploited to determine a suitable trade-off between resolution and penetration depth, a feature useful for field applications. Moreover, the tunable pulse operation of the sensor can render more target information by combining those

produced by individual operating frequency bands for certain targets.

7649-47, Session 9

A 35-GHz radar for sensing applications

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Microwave radar has been widely for sensing applications. Among the employed radars, microwave stepped-frequency radar (SFR) has several unique characteristics. Its instantaneous bandwidth at each frequency is very narrow, resulting in high signal-to-noise ratio at the receiver. Its entire bandwidth, on the other hand, can be very wide, leading to fine resolution. SFR also allows very low sampling frequency at the Analog-to-Digital Converter (ADC), hence facilitating system design. Additionally, non-linear effects caused by the inherent imperfection of the transmitter and receiver can be corrected through appropriate digital signal processing. Moreover, its high average transmitting power enables deep penetration. Microwave radars operating in the millimeter-wave regime (above 30 GHz) have several unique benefits such as light weight, small size, high accuracy and fine resolution. The main drawback of millimeter-wave radar is its small penetration depth, prohibiting its use for deep-surface sensing. It is, however, very attractive for surface and near-surface sensing.

We report new millimeter-wave stepped-frequency radar operating from 29.72 to 37.7 GHz for sensing applications. The radar is implemented using coherent super-heterodyne scheme and completely realized using microwave and millimeter-wave integrated circuits. The developed radar has been demonstrated for different sensing applications with high accuracy and resolution. It can be used for various sensing applications including pavement and bridge assessment, liquid-level measurement, detection and location of buried mines and unexploded ordnance (UXO), detection of intrusion to structures including important civil facilities, detection of slow moving objects, surveillance and monitoring of hidden activities and objects.

7649-48, Session 9

Estimation of kernels mass ratio to total in-shell peanuts using low-cost RF impedance meter

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In this study estimation of percentage of total kernel mass within a given mass of in-shell peanuts was determined nondestructively using a low-cost RF impedance meter. Peanut samples were divided into two groups one the calibration and the other the validation group. Each group contained 25 samples of about 100 g of peanuts. Capacitance, phase angle and impedance measurements on in-shell peanut samples were made at frequencies 1 MHz, 5 MHz and 9 MHz. Ten measurements on each sample set were made, to minimize the errors due to the orientation of the peanuts as they settle between the electrodes of the impedance meter, by emptyung and refilling the samples after each measurement. After completing the measurements on each set the peanuts from that set were shelled, kernels were separated and weighed. Multi linear regression (MLR) calibration equation was developed by correlating the percentage of the kernel mass in a given peanut sample set with the measured capacitance, impedance and phase angle values. This equation was used to predict the kernel mass ratio of the samples from the validation group. The fitness of the MLR equation was verified using Standard Error of Prediction (SEP) and Root Mean Square Error of Prediction (RMSEP). Also the predictability of total kernel mass ratio was calculated by comparing the mass ratio predicted using MLR model with the actual mass ratio determined using the conventional standard method of visual determination.

7649-49, Session 10

Comprehensive condition assessment of bridge decks by multimodal NDE

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Corrosion induced bridge deck delamination is a common problem in reinforced concrete decks. While condition assessment can be done using a number of traditional and NDE methods, the presented study concentrates on a complementary use of five NDE techniques: impact echo (IE), ground penetrating radar (GPR), half-cell potential (H-C), ultrasonic surface waves (USW) and electrical resistivity (ER). Each of the five techniques has its advantages and limitations. However, each of them can contribute to a more comprehensive assessment of the condition of a deck. For example, GPR can identify deteriorated bridge deck areas, while IE can accurately detect and characterize delaminations in the deck. USW, on the other hand, provides information about material degradation through a measurement of concrete elastic moduli. Finally, H-C will provide information about the likelihood for active corrosion, while ER will assess potential for corrosive environment. There are also secondary benefits of the use of the five techniques, like e.g. mapping of concrete cover from GPR surveys. A brief overview of the techniques and their complementary use illustrated by the results from deck testing on several bridges is presented. The presented surveys were conducted on both decks (typical thickness 6-8 inches) and slabs (typical thickness 14-20 inches). Results include delamination maps from IE, attenuation maps from GPR, modulus distribution maps from USW, H-C potential maps, and resistivity maps from ER. Some of the results are validated through a series of “ground truth” measurements, like inspection of cores taken from the decks and visual inspection during repairs (deck autopsies).

7649-50, Session 10

A pragmatic and innovative approach for civil infrastructure condition management: structural behavior monitoring

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In this paper, a structural behavior monitoring (SBM) based maintenance methodology is developed to combine the advantages of visual inspection and state-of-the-art instrumentation. It highly depends upon the data taken from the instrumentation in the decision-making process of infrastructure maintenance. As such, SBM must address key factors such as the ease and cost effectiveness of sensor deployment, reliability in measurement, and quality of measured data. SBM fundamentally differs from conventional structural health monitoring in focus on major failure mechanisms in structural engineering, and use of advanced distributed sensors for behavior-related or mission critical data collection from ‘hot spot’ areas or the part of a structure that will likely experience damage or significant deterioration. SBM has several unique attributes such as ‘sacrificial’ sensors, coupled measurements, and integrated monitoring and mitigation strategies. They are discussed and illustrated with an example in this paper. Example structural behaviors considered under the SBM include concrete crack and spalling, steel yielding and corrosion, member buckling, foundation scour, and fatigue.

7649-51, Session 10

Damage inspection of fiber reinforced polymer-concrete systems using a distant acoustic-laser NDE technique

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Damage detection of multilayer composite systems has been an important problem for civil infrastructure (e.g., fiber-reinforced polymer

wrapped concrete) and other engineering structures (e.g., wind turbine blades). Efficient condition assessment of the systems can be achieved if distant, rapid damage inspection techniques are available. In this paper, a distant acoustic-laser NDE technique is proposed, utilizing a high powered standoff parametric acoustic array (PAA) and laser Doppler vibrometry (LDV), for the detection of debonding and delamination in multilayer composite systems. Fiber-reinforced polymer wrapped concrete cylinder specimens with artificial defect were manufactured and used in the validation of the technique. Low-frequency (50 Hz~2 kHz) and high-frequency (2 kHz~7 kHz) focused sound waves were generated by PAA, and surface dynamic signatures of the specimens were remotely measured by LDV. From the experimental results and theoretical analysis in this study, it is found that the proposed technique successfully captures the presence of near-surface debonding/delamination.

7649-52, Session 10

The role of terrestrial 3D LiDAR scan in bridge health monitoring

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Bridges, as important part of civil infrastructures, are often large in scale and complex in performance. Most of the nation's bridges were built before or during the 1970s and they are now deteriorating at an alarming rate. Current bridge performance monitoring mostly require visual inspection, which lacks accuracy. There is an increasing need for more accurate and in-depth inspection techniques to help understanding of their health states during their service life to improve safety. Terrestrial LiDAR scanner, as a type of nondestructive, noncontact inspection technique, provides structural surface topology information as well as reflection values with high accuracy. For bridge health monitoring, it has the advantages of ease-for-operation, large area coverage, and exploitable applications. This paper discusses bridge health-related problems and the characterization of these problems using LiDAR scan. An automatic bridge inspection system based on LiDAR data, LiBE (LiDAR based Bridge Evaluation), is developed. The technique has been used for bridge structural defect detection and quantification, clearance measurement and displacement measurement in load testing. The potential applications of LiDAR data for structural strain measurement and other applications are also discussed at the end of this paper. Several bridges in Mecklenburg County, NC have been selected to be tested using the system for examples.

7649-53, Session 11

Identification and health monitoring of an instrumented building using earthquake response data

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This paper describes the identification of finite-dimensional, linear, time-invariant models of a 4-story instrumented building in the state-space representation using multiple earthquake response data sets. The building is located at the University of California, Irvine campus, and is instrumented with 43 force-balanced uni-axial acceleration sensors. Four models were constructed from multiple input and output data sets, recorded during the 2005 Yucaipa, 2005 San Clemente, 2008 Chino Hills, and 2009 Los Angeles earthquakes of varying intensity. The excellent correlation of individual model and measured responses demonstrates the effectiveness of the state-space representation in capturing the dynamic characteristics of the building during these earthquake events. Natural frequencies and damping ratios extracted from the models showed that, for the range of ground excitation considered, the response of the building was amplitude dependent with the frequency and damping ratios, for the first three modes, reducing linearly with increasing peak root mean squared ground acceleration. This linearity of response enables any of the three identified models to predict the frequencies of response and damping ratios for the fourth. The practical application of this finding is that, a rapid assessment of structural response assessment can be done for structural health monitoring purposes immediately after an earthquake event by comparing the measured response frequencies and damping ratios with those predicted based on the building response to prior earthquakes.

7649-54, Session 11

Structural behavior of a cable stayed bridge through the use of a long-term health monitoring system

Y. Cao, M. L. Wang, Northeastern Univ. (United States)

The Zhanjiang Bay Bridge is a cable stayed bridge with a main span of 480m, located in Southern China. Structural behavior due to thermal effects is presented in this paper in according to data received from a health monitoring system (HMS) since 2006. Data obtained from the analysis includes temperature gradients and time lags in the steel box girder, concrete tower, and stayed cables. These values are shown in comparison with the design specification and provide examples of the real temperature distribution and thermal behavior of long-span steel bridges. By comparing the measured and calculated thermal displacements, it was possible to estimate the unmeasured thermal gradient on the surface of the towers as well as to determine that one of the expansion joints was likely constrained and contributing to the bridges asymmetrical displacement. The results will help to implement a strategy for maintenance as well as a benchmark for future design specification.

7649-55, Session 11

Damage detection of the bridge structures using genetic algorithms

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Vibration based damage detection of the structures can be defined as an optimization problem the goal of which is to minimize the error between measured responses or characteristics of the structure and their analytically calculated counterparts. In this paper a genetic algorithms based finite element model updating technique is applied for structural damage detection from linear response of the structure to low amplitude excitations. Degradation in stiffness of the structural members is considered as damage. Stiffness modification factors of the critical structural members are found by minimizing two different objective functions defined in time and modal domains. In time domain objective function is defined as the weighted average of the mean square errors between measured and simulated responses at different sensor locations. Modal assurance criterion and relative error between experimental and analytical natural frequencies are used in definition of the objective function in modal domain.

Implemented model updating technique is applied to data recorded during a large scale shaking table test on a two-span reinforced concrete bridge. The bridge structure is subjected to a series of seismic and low amplitude white noise base excitations introducing progressive damage to the structure. Stiffness modification factors for the bents and the deck of the bridge are identified at each damage state of the structure using the recorded response of the structure to white noise excitations. Modal updating results using time and modal domain approaches are presented and compared. Results of both approaches are in good agreement with experimental damage description provided at each damage state of the structure.

Conf. 7649: Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security IV

7649-56, Session 11

Assessment of tendon duct integrity in concrete with ultrasonic imaging methods

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Tendon ducts buried in concrete may suffer from grouting defects yielding corrosion through water leakage resulting in a failure of the civil structure under concern, for instance a bridge. In principal, ultrasound can be used to locate the duct, yet an assessment of a grouting defect is only possible through sophisticated signal processing. In the present contribution we utilize tomographic imaging algorithms based on Fourier transform techniques and analyze the resulting images with respect to their phase. The technique is validated against synthetic data obtained with the Elastodynamic Finite Integration Technique (EFIT), a numerical technique to solve ultrasonic wave propagation in complex media. Applications to experimental data from test specimens and real-life structures confirm its potential.

7649-57, Session 11

Segmentation of laser range image for pipe anomaly detection

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The laser-based scanning provides a precise surface profile. It is being widely applied to the pipe inner wall inspection in conjunction with other types of sensors, like sonar and close-circuit television (CCTV). Such measurement can be used for pipe deterioration modeling and condition assessment. Laser range finder, which uses a laser beam to determine the distance to a reflective object, can be used for pipe inspection. It operates on the time-of-flight principle. A laser pulse in a narrow beam is sent out to the object and returning time of the reflected pulse is recorded. A robotic carrier can carry the laser range finder and other sensors to conduct the inspection.

Geometric information needs to be extracted to characterize anomalies in the pipe profile. Since the laser range finder measures the distance, segmentation with a threshold is a straightforward way to isolate the anomalies. However, threshold with a fixed distance value does not work well for the laser range image due to the intensity inhomogeneity, which is caused the uncontrollable factors during the inspection. Thus, a local binary fitting (LBF) active contour model is employed in this work to process the laser range image. Given an arbitrary contour at initial state, the LBF active contour based segmentation does not work well for the laser range image in this application. Therefore, an image phase congruency algorithm is adopted to provide the initial contour as required by the LBF method. The combination of these two approaches can successfully detect the anomalies from the laser range image.

7649-58, Session 11

Monitoring early age microstructure development of cementitious materials using bender elements

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Current approaches to measuring early age mechanical properties (shear modulus and viscosity) of fresh concrete are based on rheological measurements, which require expensive equipment and trained personnel. The conventional ultrasound transducers are not effective to generate and transmit shear waves in fresh concrete due to the low shear modulus. This paper proposed using piezoelectric bender elements to generate and measure shear waves in early age cementitious materials. The bender elements have been widely used for measuring shear wave velocity Vs of soils, even for Vs as low as 20m/s. However, application of bender elements to cementitious materials has not been reported. Based on the measured shear wave velocity, the setting time of cementitious materials can be determined when the shear wave velocity starts to increase. Then shear modulus and viscosity of the tested material can also be derived from the measured shear wave velocity and attenuation. Finally, measurements from the bender elements setup were compared and related to the Vicat and rheometric test results.

7649-59, Session 11

Efficient analysis of response variation in mistuned periodic structures using order reduction

J. Tang, Univ. of Connecticut (United States)

Engineering structures, at their healthy condition, are inevitably subject to manufacturing tolerance and normal in-service property change. Analyzing the response variation in engineering structures has obvious significance, as it establishes the threshold for vibration-based damage detection. However, for complex structures, a credible finite element model has very high dimension, which leads to high computational cost in dynamic analysis even for the deterministic case. As the characterization of mistuning usually involves Monte Carlo type sampling, combining random sampling with high dimensional structural dynamic analysis generally renders insurmountable computational costs. In this research, we explore an efficient uncertainty analysis that is built upon the order reduction utilizing the component mode synthesis technique. It is found that the free-interface approach can facilitate efficient probabilistic dynamic analysis. The newly established algorithm is applied to periodic structures (e.g., bladed-disks in aero engine and turbomachinery) with mistuning. The means and variances of modal responses are analyzed and verified.

7649-60, Session 11

Damage detection of a condensation pipeline joint in-service

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The early detection of damage in structural or mechanical systems is of vital importance. With early detection, the damage may be repaired before the integrity of the system is jeopardized resulting in monetary losses, loss of life and limb, and environmental impacts. Among the various types of structural health monitoring techniques, vibration-based methods are of significant interest since the damage location does not need to be known beforehand, making it a more versatile approach. The non-destructive damage detection method used for the experiments herein is a novel vibration-based method called the EMD Energy Damage Index developed with the aim of providing improved qualitative results compared to those methods currently available. As part of an effort to establish the integrity and limitation of this novel damage detection method, field testing was completed on a mechanical pipe joint on a condensation line, located in the physical plant of Dalhousie University. Piezoceramic sensors, placed at various locations on and around the joint were used to monitor the free vibration of the pipe imposed through use of an impulse hammer. Multiple damage progression sessions were completed, each having a healthy state and multiple damage cases. Subsequently, the recorded signals from the healthy and damaged pipe joint were processed through the EMD Energy Damage Index developed in-house in an effort to detect the inflicted damage. The proposed methodology successfully detected the inflicted damages. In this paper the effect of impact location, sensor location, frequency bandwidth range, intrinsic mode function, and boundary conditions is discussed.

Conf. 7649: Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security IV

7649-61, Session 11

Combined use of thermography and ultrasound for characterization of subsurface cracks in concrete

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Subsurface damage in concrete may develop due to many reasons like corrosion of the reinforcing bars. Usually it can be identified only after breaking the surface. In the present study steel fiber reinforced concrete specimens with subsurface cracks developed after four point bending test were examined by passive thermography after being heated in an oven. The subsurface cracks cause faster cooling locally and leave their marks on the temperature field and the cooling curve highlighting the damaged area. Specific descriptors are also applied for the cases where visual examination of the thermogram is not positive due to other surface defects like porosity, air bubbles etc. Consequently, ultrasonic one-sided measurements take place in order to characterize the specific area in detail. Parameters such as the velocity and amplitude of the Rayleigh wave measured at different locations are correlated with the thickness of the healthy material under the surface, while the frequency is varied in order to alter the penetration depth. It is concluded that the combination of thermography and ultrasonic measurements provides a quick and non intrusive way of detecting subsurface damage which can be applied in real structures.

7649-76, Session 11

Ultrasonic wave attenuation measurement for nondestructive evaluation of concrete

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Various nondestructive evaluation methods using the propagating velocity and attenuation of an ultrasonic wave have been studied. The ultrasonic wave attenuation is more sensitive on evaluating to damage assessment in the medium than the ultrasonic wave velocity method. In this paper, the nondestructive evaluation technique using self-compensating frequency response function is proposed to measure the quantitative ultrasonic wave attenuation on cement-based materials. The proposed technique is able to measure inherent attenuation of material, not its relative attenuation. In advance, the repeatability and relevancy of proposed technique are validated by an experimental comparison of conventional measurement and proposed ultrasonic wave attenuation measurement on cement paste. In addition, the ultrasonic attenuation measurements are used to characterize the size distribution and volume fraction of entrained air voids in cement-based materials.

Conf. 7650: Health Monitoring of Structural and Biological Systems IV

Monday-Thursday 8-11 March 2010

Part of Proceedings of SPIE Vol. 7650 Health Monitoring of Structural and Biological Systems 2010

7650-01, Session 1a

Comparison of 1D and 3D laser vibrometry measurements of Lamb waves

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This purpose of this paper is to compare and contrast 3D and 1D laser vibrometry measurements of piezo-generated Lamb waves in thin aluminum plate. Due to the large cost and capability difference between 1D and 3D laser-based measurement systems, this study presents the benefits and challenges of each measurement approach. The primary reason for using a state-of-the-art 3D laser-based measurement system is that it provides the capability to make non-contact surface velocity measurements over a spatially dense grid resulting in consistent and accurate measurements of Lamb waves propagating through a plate. Experiments are performed on a 1 mm thick plate in which a 100 volt peak-peak Hanning-windowed 5 ½ cycle sine wave and 200 volt 5 µs pulse excitation signals are applied to either a single piezo-actuator or a pair of piezo-actuators mounted on oppositely on each side of the plate. The intent of the pulse signal is to excite a wide range of frequencies so a broader range of analysis can be performed. The evaluation of the 1D and 3D measurement techniques will compare the propagation characteristics (dispersion, time-of-flight, mode amplitude, etc.) primarily of Lamb wave modes S0 and A0, however, higher modes are evaluated due to high excitation frequencies. Because in-plane measurements are collected, faster longitudinal wave components can be measured and compared to the the slower out-of-plane shear components. A predefined mesh and coordinate system is provided resulting in high spatial resolution and repeatable measurements. The spacing between measurement points is 1mm, and the grid has over 30,000 measurement points. All data is collected using the high frequency PSV-400-3D-M scanning laser vibrometer. This paper shows that both 1D and 3D non-contact laser Doppler velocimeter measurements can lead to a much higher level of understanding of Lamb wave propagation and interaction with structural variations.

7650-02, Session 1a

Time series analysis of piezoelectric active-sensing for SHM applications

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In this paper, the use of time domain data from piezoelectric active-sensing techniques is investigated for structural health monitoring (SHM) applications. Piezoelectric transducers have been increasingly used in SHM because of their proven advantages. Especially, the use of known and repeatable inputs makes the development of SHM signal processing algorithm easier and more efficient. However, to date, most of these techniques have been based on frequency domain analyses, such as impedance-based or high-frequency response functions (FRF)-based SHM techniques. Even with Lamb wave propagations, most researchers adopt frequency domain or wavelets analysis for damage-sensitive feature extraction. This process usually requires excessive averaging to reduce measurement noise and more computational resources, which is not ideal from both memory and power consumption standpoints. Therefore in this study, we investigate the use of autoregressive models with exogenous inputs (ARX) with the measured time series data from piezoelectric active-sensors. The test structures considered in this study include a section of CX-100 wind turbine blade and a 2 x 2 ft composite plate, where the plate was subjected to a series of impact loadings to induce damage in the form of fiber delimation. The performance of the proposed technique is compared to that of traditional autoregressive (AR) models, traditionally used in low-frequency passive sensing techniques, and that of FRF-based analyses, and its superior capability in SHM is demonstrated. This paper outlines the advantages of this method over traditional frequency-domain analyses and provides guidelines for using time-series data from active-sensors for real-world SHM applications.

7650-03, Session 1a

Detection of delamination defects in carbon fiber reinforced polymer components: miniaturized hardware design for the smart material actuation of ultrasound guided waves

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This contribution is concerned with the hardware design of a structural health monitoring (SHM) system for continuous delamination detection in carbon fiber reinforced polymer (CFRP) components. A CFRP plate under test is equipped with an integrated actuator array of eight piezoelectric patches which are driven by miniaturized high frequency power amplifiers. The line array is capable of emitting directional guided Lamb waves with a frequency of several hundreds of kilohertz. An onboard microcontroller enables the selection of the waveform pattern and the emitted direction. The directivity of the Lamb wave depends on the phase difference between the individual actuator signals. An appropriate resolution of directivity (5° at 250kHz) is provided by the underlying miniature electronics. With subsequent scanning in several directions a larger area on the CFRP test specimen (approx. 600mm x 600mm) is covered. Delamination defects are induced by accurately defined impact damages. A laser scanning Doppler vibrometer is used to visualize the propagation of the corresponding Lamb waves, as well as reflections which are caused by delamination defects. A small number of laser measurement points form a virtual sensing array. Due to the scanning process defective areas (approx. 17mm x 17mm) are detected and can be located by time of flight measurements. The results can be evaluated by a 2-D representation of the localized impact damages. The hardware platform provides a portable system for the investigation of real world components, e.g. aircraft CFRP structures.

7650-04, Session 1a

Lamb wave sensing with metal-core piezoelectric fiber for structural health monitoring

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Metal-core piezoelectric fibers (MPF) are a new type of piezoelectric ceramic device with small size, and have great potential to be used as structurally integrated transducers for guided-wave (GW) structural health monitoring. Their main advantages over conventional monolithic wafer transducers are the smallest functional influence to structure, curved surface conformability, power efficiency, and their unidirectional sensing capability as a GW sensor. This paper presents MPF for Lamb sensing, and structural damage location. Equations for the output voltage response of surfaced-bonded MPF sensors in Lamb-wave fields are derived and optimization of the MPF sensor dimensions is performed based on these equations. Then, the obtained simulation result is validated on an aluminum plate. The comparison between predictions and measurement is rather satisfactory in terms of both relative amplitude and spectral shape. Furthermore the results show that the capability of MPF sensors to sense Lamb waves is critical

for practical structural health monitoring (SHM) applications such. as impact and damage localizations. The good directional properties of MPF are used to determine the direction of the reflected Lamb waves by mounting three MPF sensors in a rosette configuration in analogy to the well-known electrical resistance strain gage rosette. The performance of the rosettes for damage localization is validated on an aluminum plate. The results show very good agreement between the calculated and actual positions of damage.

7650-05, Session 1b

Health monitoring of prestressing tendons in post-tensioned concrete structures

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The use of original design solutions and innovative materials introduces always new challenges. For example, newly designed aircrafts where there is an extensive use of composite materials are particularly vulnerable to impacts because susceptible to damage when severely loaded out of plane such in the case of localized impacts (i.e. hail ice impacts). Structural health monitoring systems able to detect and quantify impact related defects could be beneficial in innovative aerospace structures providing information on the condition of the structure in real-time.

Many studies have demonstrated that the peak amplitude of the impact force is correlated to the damage induced in composite structural components hence the importance of a technique able to estimate the impact force. The force identification represents an inverse problem. The present paper deals specifically with the problem of identification of impact forces on isotropic and composite panels.

First a semi analytical finite element (SAFE) approach is employed to predict the frequency response and time history response of MFC sensors assuming an impulse force excitation. Subsequently, the impact force is estimated updating the force time history assumed in the SAFE by minimizing the difference between numerical and experimental signals from MFC sensors. Such procedure has been used in isotropic and composite plates. Impact forces generated using impact hammers and different ice projectiles launched with gas cannon on panels have been identified.

7650-06, Session 1b

Bridge monitoring using heterogeneous wireless sensor network

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Wireless sensor networks (WSN) are proving to be a good fit where real time monitoring of multiple physical parameters is required. In many applications such as structural health monitoring, patient data monitoring and traffic accident monitoring and analysis, sensor networks may involve interface with conventional P2P systems and it is challenging to handle heterogeneous network systems. Heterogeneous deployments will become increasingly prevalent as it allows for systems to seamlessly integrate and interoperate especially when it comes to applications involving monitoring of large infrastructures. Such networks may have wireless sensor network overlaid on a conventional computer network to pick up data from one distant location and carry out the analysis after relaying it over to another distant location.

This paper discusses monitoring of bridges using WSN. As a test bed, a heterogeneous network of WSN and conventional P2P together with a combination of sensing devices (including vibration and strain) will be used on a bridge model. Issues related to condition assessment of the bridge for situations including faults, overloads, etc., as well as analysis of network and system performance will be discussed. When conducted under controlled conditions, this is an important step towards fine tuning the monitoring system for recommendation of permanent mounting of sensors and collecting data that can help in the development of new methods for inspection and evaluation of bridges. The proposed model and design will be discussed, along with its implementation and results.

7650-07, Session 1b

Multi input-single output (MISO) models identification of tower bridge movements using GPS monitoring system

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In this paper, RTK-GPS system was used for displacements data collection. Two identification models namely; Multi Input-Single Output (MISO) robust fit regression and Neural Network Auto-Regression Moving Average with eXogenous input (NNARMAX) models were used for the identification of these data. The analysis of test results indicate that: (1) the traffic loads are the main factor affects tower bridge displacement, (2) the NNARMAX[4411] and [5415] models defined by taking into account the results of robust regression analysis estimate structural movements more accurately than the NNARMAX[0100] model, and (3) The robust fit regression models have good capacities for mapping relationship of applied loads effects factors and displacements of tower. However, temperature and humidity effects on the entire modal shapes are insignificant.

7650-08, Session 1b

Correlation analysis and application of the bridge structural health monitoring system

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Bridge structural health monitoring system is a typical multi-sensor measurement system due to the multi-parameters of bridge structure collected from the monitoring sites on the river-spanning bridges. For the present bridge structural health monitoring system, especially those long-span systems, data measurement system is invariably composed of hundreds of sensors which are distributed in different monitoring sites. However, Bridge structure monitored by multi-sensors is an entity, When subjected to external action, there will be different performances to different bridge structure parameters. Therefore, the data acquired by each sensor should be exist countless correlation relation. Because the bridge structure is a complex system, the each sensor data of the health monitoring system all is the response output of the bridge. Traditionally correlation analysis among monitoring sites is mainly considered from physical locations. Unfortunately, this method is so simple that it can not describe the correlation in detail. The paper analyzes the correlation among the bridge monitoring sites according to the bridge structural data, defines the correlation of bridge monitoring sites and describes its several forms, then integrating the correlative theory of data mining and signal system to establish the correlation model to describe the correlation among the bridge monitoring sites quantificationally. Finally, The Chongqing Mashangxi Yangtze river bridge health measurement system is regards as research object to identify continuous invalid data, and simulation results verify the effectiveness of the designed method and theoretical discussions.

7650-09, Session 2a

Use of anisotropy to guide acoustic waves along desired trajectories

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Acoustic stress waves can be guided to follow pre-determined paths in solids, using material anisotropy but homogeneous mass density. Recently, there has been intense interest to design materials (generally referred to as metamaterial) that can shield specific regions within the material by redirecting the incident stress-waves along desired paths. Some of the proposed techniques involve variable mass density and stiffness that are unrealistic. We have designed a material with isotropic

mass density but highly anisotropic elasticity that can guide incident waves along desired trajectories.

For a transversely isotropic material, the axis of anisotropy (normal to the plane of isotropy) can be adjusted to direct the group velocity-vector along a given trajectory. In a fiber-reinforced composite, the elastic modulus along the fiber direction is much greater than that in the transverse direction. Hence, by choosing a suitable fiber direction, we can create a medium that can redirect quasi-longitudinal waves in the direction of the highest stiffness. A novel design of anisotropic fiber-reinforced composite materials is suggested in which the glass fibers follow smooth trajectories. Harmonic excitations are imposed, and it is shown that the stress-wave energy would travel around a desired central region and is then measured on the opposite face of the sample. The model is first designed using numerical simulations, and then fabricated and tested. Further numerical analysis confirms that a great portion of the stress-wave energy is guided around the central cavity and is delivered almost to a location that corresponds to the location where the incident excitation is imposed.

7650-10, Session 2a

A new algorithm for detecting impact points in anisotropic plates by the acoustic emission technique

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The wave speed in an anisotropic plate is dependent on the direction of propagation and therefore the conventional triangulation technique does not work for predicting the impact point in composite plates. A method based on the optimization technique has been proposed by Kundu et al. (2007) to detect the point of impact in an anisotropic plate. The objective function uses the time of flight information of the ultrasonic signals to the passive transducers attached to the plate and the wave propagation direction ( ). This objective function is very sensitive to the arrival times and a small variation in any one arrival time results in a significant change in the impact point prediction. This shortcoming is overcome here by modifying the objective function and following a new algorithm using both old and new objective functions. The new algorithm uses several transducers and looks at the common region of predictions from different sets of transducers. This algorithm is less sensitive to the arrival time variation and thus is capable of predicting the impact location correctly even when the measured arrival time has some error. The new objective function is simpler, so the code run time is reduced and it is less likely to converge to the local minima when using the simplex or other optimization techniques. The new algorithm has been used to predict the impact point using both new and old objective functions and the results are compared with experimental results.

Reference:

Kundu, T., S. Das and K. V. Jata, “Point of Impact Prediction in Isotropic and Anisotropic Plates from the Acoustic Emission Data”, Journal of the Acoustical Society of America, Vol. 122 (4), pp. 2057-2066, 2007

7650-11, Session 2a

Mode elective excitation and detection of Lamb waves

K. Hahn, U. Amjad, K. S. Tarar, W. Grill, Univ. Leipzig (Germany)

Transducer arrangements including specially designed electronic drive and detection circuitry are presented, suitable to distinguish between the orthogonal symmetric and antisymmetric Lamb wave modes. Whereas transducers mounted on both surfaces have already been introduced for this task, novel schemes based on transducers mounted single sided are exemplified in combination with advanced electronic schemes providing alignment with respect to the orthogonality of the to be separated modes. Details of the developed schemes are exemplified together with experimental results which are compared to the expectations based on established modeling.

7650-12, Session 2a

Active loose bolt detection in a complex satellite structure

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This work focuses on the detection, localization, and quantification of damage in the form of loose bolts on an iso-grid satellite structure. In the process of rapid satellite development and deployment, it is necessary to quickly complete several levels of validation tests. Structural Health Monitoring methods are being investigated as means for reducing the number of validation tests required. In this paper, a method for detecting loose bolts that enables quick confirmation of proper assembly, and verification that structural fasteners are still intact after validation testing is considered. Within this testing framework, feature selection is presented, as well as a localization methodology. Quantification of fastener torque is also developed. Locating damage in an iso-grid structure is complicated by the directionally dependent dispersion characteristics caused by a propagating wave passing through ribs and holes. For this reason, an actuation frequency with the best differentiation between the dominant modes is selected. A methodology is presented in which a time map is constructed for each actuator-sensor pair which establishes times of flight for each location on the sample. Differences in time between healthy and damaged sensor signals are then extracted and used to create a map of possible damage locations. These resulting solution maps are merged, yielding a final damage position. Initial results show that the loose bolt can be located and its torque can be quantified.

7650-13, Session 2a

Warped frequency transform for damage detection using Lamb waves

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The use of Lamb waves for structural health monitoring (SHM) has interested many researchers. Nevertheless Lamb-wave testing for SHM is complicated by the dispersive nature of wave modes. The dispersion deteriorates the wave spatial resolution, makes the experimental data hard to interpret, and limits the selection of Lamb wave operating frequencies.

This paper presents a novel and low-computational cost time-frequency procedure called warped frequency transform (WFT) to process multi-mode and dispersive Lamb waves for damage detection. The WFT is based on time-frequency domain tilings chosen to match dispersion curves of different wave modes and reshape the frequency axis. It is capable of converting a dispersive wave into its incipient shape at a spatial location proportional to its traveling distance, and thus fully compensating the dispersion effect. The technique was first tested in simulations. Dispersive waves are obtained from an Al plate model with four different depth of notches by means of finite element simulations. After applying the WFT, warped waves recovered both wave shapes and spatial locations. Second, the WFT was tested on experimental data recorded by a scanning laser Doppler vibrometer from a 3-mm thick Al plate with a single source and one damage emulated by a mass block. Both the raw data and the warped data are fed to classical triangulation procedure to image the damage. The comparison between the resulting images shows that the WFT is able to removal the dispersion effect and improve the localization of the damage. Figure 1 shows example images of a source by using the proposed algorithm.

7650-14, Session 2b

A statistical confidence model for noise-contaminated structural transmissibility measurements used in damage detection

Z. Mao, M. D. Todd, Univ. of California, San Diego (United States)

For structural health monitoring, the transmissibility between two response measurements is a widely-used feature for damage detection and localization. In real practice, the transmissibility estimate is always obtained from noise-contaminated measurements on both channels. This noise can lead to reduced sensitivity in the transmissibility as a damage-sensitive feature and to false-positive (Type I) errors in its interpretation. In this paper, a model is established to investigate the effect of noise and establish statistical confidence limits on the transmissibility estimate. We make the assumption that the system is stationary, the signal channels are optimized, and the signal-to-noise ratios are balanced. The analytical expressions of the biased error and variation are given in terms of coherence estimation, and the confidence bounds of the transmissibility with corresponding level of confidence are estimated. The paper compares the analytical bounds derived for Gaussian noise to number of observed outliers in simulated and experimental data.

7650-15, Session 2b

Damage inspection and health monitoring of dynamical systems by advanced time-frequency analysis

P. F. Pai, Univ. of Missouri-Columbia (United States)

This paper presents an advanced time-frequency analysis technique based on the empirical mode decomposition (EMD) and a newly developed conjugate-pair decomposition (CPD) method for damage detection and health monitoring of dynamical systems. Responses of damaged dynamical systems are often nonlinear and nonstationary. EMD uses the apparent time scales revealed by the signal's local maxima and minima to sequentially sift components of different time-varying scales, starting from high-frequency to low-frequency ones. Because EMD does not use predetermined basis functions and function orthogonality for component extraction, it decomposes a nonlinear nonstationary signal into just a few physically meaningful components. Then, CPD uses one or more pairs of windowed regular harmonics and function orthogonality to track time-varying frequency and amplitude of each component extracted by EMD. Because CPD processes only time-domain data, it reduces the end effect caused by Gibbs' phenomenon and other mathematical and numerical problems caused by the use of Hilbert transform. Hence, results from CPD are valuable for accurate parametric and non-parametric identifications of mechanical systems. For parametric identification, the method compares the time-varying frequency and amplitude from CPD with those from perturbation analysis to determine the type and order of nonlinearity and system parameters. For non-parametric identification, the method uses the maximum displacement states to determine the displacement-stiffness curve and the maximum velocity states to determine the velocity-damping curve. Numerical and experimental results show that the proposed method can provide accurate parametric and non-parametric identifications, damage detection, and health monitoring of different linear/nonlinear dynamical systems.

7650-16, Session 2b

Lumped circuit mechanical models and lattice dynamics approach to the dependence of the time-of-flight of bulk and guided acoustical modes on elongation

K. S. Tarar, U. Amjad, W. Grill, Univ. Leipzig (Germany)

On the basis of different first principle approaches as used for lattice dynamics basic features of the dependence of the time-of-flight of acoustic waves are treated and exemplified. It is demonstrated that different effects leading as well to a reduction as to an increase of the to be observed time-of-flight can be present depending on the actual mode respectively polarization and the boundary conditions involved. Whereas geometrical stiffening will lead to a decrease of the time of flight under extensional stress, anharmonic effects will normally cause a softening and lead to an increase. Different approaches based on lattice dynamics and mechanical lumped circuits are compared with results obtained by continuum mechanics. Applications involving stress respectively strain detection and monitoring of the load dynamics are exemplified.

7650-17, Session 2b

Characterization of acoustic emission signals generated during fretting

M. J. Sundaresan, M. T. Alam, North Carolina Agricultural and Technical State Univ. (United States)

Acoustic emission (AE) based structural health monitoring (SHM) has the potential for real time detection of damage growth in critical regions of structures. However, one of the major problems in the implementation of the AE based SHM is the presence of extraneous noise which results in unacceptable levels of false positives. An important source of such false positives is the generation of acoustic emission signals by the fretting of contact surfaces. When surfaces such as those in riveted lap joints are subjected to cyclic loading, there is a small relative movement in the lap area, of the order of about 20 to 100 micrometers, which causes fretting. Unfortunately, this is also the region where we expect fatigue crack growth and hence it is not possible to use conventional time delay based techniques to separate the two types of AE signals. This paper uses numerical simulation of the fretting process and the resulting AE signals in plates with an objective of developing techniques to differentiate damage related AE signals from fretting related AE signals.

The surfaces under consideration have microscopic roughness, commonly characterized as a statistical distribution of asperity heights with certain radius of curvature. When two such surfaces are in contact, the real contact is between the relatively large asperities of the two surfaces, which undergo deformation due to normal load. When one surface slides over the other, asperities of this surface successively collide with those in the other surface, resulting in rapid local loading and unloading of asperities. Usually a numbers of asperities on the two surfaces collide during the fretting process, within the short duration of a fretting related slide. The rapid release of strain energy associated with these collisions result in stress waves in the structure that are sensed as acoustic emission signals. The normal and tangential transient forces causing these acoustic emission signals are governed by the contact mechanics of these surfaces.

In this analysis Greenwood and Williamson's model is used to determine the contact forces. The simulations included various combinations of fretting conditions. They included different combinations of surface roughness, contact pressures, sliding distances, sliding velocities, and different sensor locations relative to the fretting region. It is found that fretting generated AE signals are quite indicative of the underlying fretting process. For example, the frequency content, amplitude, and duration of the AE signals generated by relatively smooth surfaces is distinct from the signals generated by rough surfaces. More importantly, the fretting signals can be distinguished from the damage related AE signals, once the fretting signal characteristics are established. The results from the numerical simulations confirm that the fretting related signals have longer duration and rise time, but have predominantly lower frequency content. However, the frequency content in of fretting related AE signals can overlap those in the damage related AE signals. Examples of damage related acoustic emission signals and fretting related signals from both numerical simulations as well as experimental results will be presented.

7650-18, Session 2b

Electromagnetic wave modeling in a coaxial cable with multiple apertures

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Coaxial cable sensors are composed of inner and outer conductors (steel spirals) as well as dielectric layer in between. In this study an electromagnetic model is developed to investigate the effects of small aperture on a cable sensor. The primary objective of this study is to derive an analytical solution for the propagation of electromagnetic waves in a coaxial cable with a small surface aperture from the Maxwell equation, validate with the testing of a commercial coaxial cable, and apply it for the assessment of concrete-sensor interfacial condition. The test data from simply-supported RC beams were used as a test bed for structural assessment application. The simulations indicated that the reflection coefficient due to an aperture on the coaxial cable mainly depends on the length of the aperture that is projected to the cross sectional plane of the cable. The simulation results are in good agreement with the test data.

7650-19, Session 3a

Damage visualization via beamforming after frequency-wavenumber filtering of full wavefield data

M. Ruzzene, B. Xu, S. J. Lee, T. E. Michaels, J. E. Michaels, Georgia Institute of Technology (United States)

Lamb waves have great potential for damage detection in plate-like structures, and imaging using Lamb waves provides a direct way to detect and characterize structural damage. A number of methods have been developed to visualize damage, including spatially compact phased arrays, spatially distributed arrays, full-wavefield imaging, and Lamb wave tomography. The development of effective damage imaging and characterization tools is a challenging task because of the dispersive and multi-modal nature of Lamb waves. An additional problem is the need for baseline data that is required by a number of existing techniques.

This paper presents the development of damage imaging algorithms applied to filtered wavefield data received from one or more piezoelectric disc sources. Frequency-wavenumber filtering is used to both remove incident waves and separate individual wave modes. Filtered data, which contain residual, single mode signals, are input to imaging algorithms that detect damage, estimate its location, and characterize its scattering behavior. The implementation of incident wave removal procedures avoids the need for a baseline, while mode separation permits the analysis of modes that are most sensitive to damage. The sensitivity of the detection scheme and the quality of the images obtained rely on the wealth of information provided by full wavefield measurements, which can be exploited to test several array configurations. In the proposed approach, delay-and-sum beamformers are applied and tested for array topologies that are optimized for optimal damage visualization.

7650-20, Session 3a

Computational Lamb wave model validation using 1D and 3D laser vibrometer measurements

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Lamb waves are being explored for structural health monitoring (SHM) due to the capability of detecting relatively small damage within reasonably large inspection areas. However, Lamb wave behavior is fairly complex and therefore various computational techniques, including finite element analysis, have been utilized to design appropriate SHM systems. Validation of these computational models is often based on a limited number of measurements made at discrete locations on the structure. For example, models of pitch-catch of Lamb waves may be validated by comparing predicted waveform time histories at the received sensor to experimentally measured results. The use of laser vibrometer measurements offers the potential to improve model validation. One-dimensional (1D) laser vibrometer scans provide detailed out-of-plane measurements over the entire scanned region and checks at the discrete sensor locations can still be performed. The use of three-dimensional (3D) laser vibrometer scans further expands the data available for correlation by providing velocity components over the entire scanned region. This paper discusses the use of 1D and 3D laser vibrometer data for validating models of healthy and damaged plates. Cracking in metallic structures, as well as delamination and impact damage in composite structures, are considered.

7650-21, Session 3a

In situ PZT diagnostics using linear reciprocity under environmental and structural variations

S. J. Lee, J. E. Michaels, T. E. Michaels, Georgia Institute of Technology (United States); H. Sohn, Korea Advanced Institute of Science and Technology (Korea, Republic of)

Guided waves generated by a spatially distributed array of piezoelectric transducers such as Lead Zirconate Titanate (PZT) are being considered to investigate structural integrity for structural health monitoring applications. It is generally assumed that these surface-mounted PZT transducers are both undamaged and properly bonded to the host structure during usage. However, this assumption may not be valid, particularly after long term operation under realistic conditions. Existing transducer diagnosis techniques, such as the electromechanical impedance method, often identify PZT defects by comparing current data obtained from a potentially damaged PZT transducer to baseline data previously measured from the pristine condition of the bonded transducer. However, this baseline-dependent approach can result in false alarms because of its susceptibility to operational, structural and environmental variations.

In this study, a methodology for PZT transducer diagnosis is developed to identify abnormal transducers by quantifying the degree of linear reciprocity for waves propagating between pairs of surface-mounted transducers on metallic structures. The proposed method does not require direct comparisons of signals to baselines, and also is independent of wave modes, structural complexity and edge reflections. Abnormal PZT transducers can be detected even when the system being monitored is subjected to varying operational, environmental or structural conditions. In addition, it is expected to be effective for more complex structures both with and without structural damage. The feasibility of the proposed diagnostic technique is evaluated via numerical simulations and experiments with PZT transducers instrumented on an aluminum plate under varying environmental and structural conditions.

7650-22, Session 3a

Guided waves for SHM of large truss structures

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This paper describes a method based on Ultrasonic Guided Waves (UGWs) for the detection of cracks in sign support structures. The method combines the advantages of UGWs with the outcomes of the Discrete Wavelet Transform (DWT) to extract defect-sensitive features aimed at performing a multivariate diagnosis of damage. The general framework presented in this paper is applied to ultrasonic data collected from a dismantled overhead sign structure tested at the University of Pittsburgh. The probing hardware consists of a National Instruments-PXI platform that controls the generation and detection of

the ultrasonic signals by means of piezoelectric transducers made of Lead Zirconate Titanate. The effectiveness of the proposed approach to diagnose the presence of defects as small as a few percent of the waveguide cross-sectional area is demonstrated.

7650-23, Session 3a

Delamination detection in composite structures using laser vibrometry measurements of Lamb waves

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In this study, the feasibility of using a scanning laser vibrometer for detecting hidden delamination in multi-layer composites is explored. First, Lamb waves are excited by Lead Zirconate Titanate (PZT) transducers mounted on the surface of a composite plate, and Lamb wave velocities are measured using 1D and 3D scanning laser vibrometers. From the scanned velocity time signals, wave field images are constructed and processed to highlight the interaction of Lamb waves with hidden delamination. Furthermore, the effects of the input waveform, driving frequency, directionality of wave propagation and selective mode excitation on delamination detectability are investigated using experimental data collected from a 1.8mm thick multi-layer composite plate and a 15mm thick composite wing structure

7650-24, Session 3a

Reference-free impedance-based crack detection in plate-like structures

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Conventional impedance-based damage detection techniques identify damage by comparing “current” impedance signals with “baseline” ones obtained from the pristine condition of a structure. However, in reality, structures are subject to changing environmental and operational conditions that significantly affect measured impedance signals and these ambient variations can often cause frequent false-alarms. A new reference-free impedance-based damage diagnosis, which does not require direct comparison with baseline impedance signals, is developed for crack detection in a plate-like structure. In order to reduce the possibility of false-alarms due to operational and environmental variations, the proposed method utilizes a single pair of PZTs collocated on the both surfaces of a structure to detect mode conversion effects caused by the presence of crack damage. A new statistical damage classifier is developed for instantaneous damage classification based on decomposed impedance signatures containing mode conversion information. Tests of temperature variation and ambient vibration are conducted to examine the validity of the proposed technique. Experimental results are presented to demonstrate the applicability of the proposed method to crack detection.

7650-25, Session 3a

Defect detection using a new ultrasonic guided wave modal analysis technique (UMAT)

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A new ultrasonic guided wave modal analysis technique (UMAT) is being studied to bridge the gap between ultrasonic guided wave methods and lower frequency vibration modal analysis methods for Nondestructive Evaluation (NDE) and Structural Health Monitoring (SHM). The new technique provides improved defect detection sensitivity superior to modal analysis alone, and, at the same time, reduces the number of inspection positions required by the guided wave techniques for a complete coverage of the structures being inspected. Instead of focusing on the transient structural response to a guided wave input, the proposed UMAT puts the emphasis on the long time structural response to a specifically defined ultrasonic guided wave input. Since different guided wave modes and frequencies yield good sensitivities to different kinds of defects, the specified guided wave input which is selected to target on a certain defect type provides a special sensitivity to the defect type. By varying the input guided wave modes and frequencies, good sensitivities to all different kinds of defects can be achieved. In UMAT, the defect information is extracted through modal analyses on the long time structural responses to the controlled guided wave inputs. Thanks to the fact that the long time structural responses result from multiple reflections and scatterings of the input guided wave energy, an overall coverage of the structure can be reached from a very limited number of tests. UMAT is also capable of inspecting odd shaped parts with different attachment considerations or boundary conditions and even hidden, coated, or insulated parts as long as a small section is accessible.

7650-26, Session 3b

In-service monitoring of steam pipe systems at high temperatures

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An effective system is needed for in-service monitoring of steam pipes. The system is required to measure the height of the condensed water inside the pipe while operating at temperatures as high as 250oC. For this purpose, ultrasonic waves are used to perform the required sampling and signal processing to allow for real time measurements while accounting for various effects such as water flow and others. Transmitting and receiving the waves is done by piezoelectric transducers having high Curie temperature that can sustain the high temperature level over extended operation period. The challenges to operate the transducers at such high temperatures and perform ultrasonic measurements are addressed and the results of the study will be covered in this paper.

7650-27, Session 3b

A guided wave technique for detection of gas accumulation in piping systems

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Accumulation of gas in water filled cooling systems is a significant issue for the nuclear power industry. Gas voids have the potential to cause pumps to bind and reduce reliability of safety cooling systems. Currently, there is a need for a technique which can quantify gas accumulation in a piping system. This study investigated the use of ultrasonic guided waves to detect and quantify gas accumulation. Modes were tested on a mockup of an industrial piping system comprised of 65 ft. of 6” stainless steel pipe including two elbows, two bends, and three welds. The mockup was filled with water, water was gradually removed in one percent volume increments to conduct guided wave experiments. Experiments were conducted with multiple modes by employing variable angle wedges and frequency sweeping to sweep through the dispersion space. Modes were tested to determine the amount of leakage into the pipes with various levels of water. L(0,1) mode at 450 kHz provided the optimal sensitivity and signal-to-noise ratio. Various array configurations were investigated. A technique using a small array of three fixed angle wedges was found to produce the optimal sensitivity.

7650-28, Session 3b

Behavior of full-scale concrete segmented pipelines under permanent ground displacements

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Concrete pipelines are one of the most popular underground lifelines that transmit water resources. Unfortunately, this critical infrastructure system remains vulnerable to ground displacements during seismic and landslide events. Ground displacements may induce significant bending, shear, and axial forces to concrete pipelines and eventually lead to joint failures. In order to explore the typical failure mechanisms of concrete segmented pipelines, large-scale experimentation is necessary to explore the structural and soil-structure behavior. This paper reports on the experimentation of a reinforced concrete segmented concrete pipeline using the unique capabilities of the NEES Lifeline Experimental and Testing Facilities at Cornell University. Five full segments of a full-scale commercial concrete pressure pipe (244 cm long and 37.5 cm diameter) are constructed as a segmented pipeline under a compacted granular soil in the test basin (13.4 m long and 3.6 m wide). Ground displacements are simulated through translation of half of the test basin. A dense array of sensors including potentiometers, strain gauges, and load cells are installed along the length of the pipeline to measure the pipeline response to ground displacement.

7650-29, Session 3b

Rayleigh surface waves for characterization of porosity in fresh concrete

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The durability of concrete pavement to freeze/thaw cycles is dependent on porosity. Air entrainment admixtures are used to provide the desired air void system. The best performance is provided by an air void system that has air content, spacing factor, and specific surface parameters within specifications. Large entrapped air voids are detrimental to thermomechanical behavior of concrete and make it insufficient to simply characterize the porosity by the air content. Ability to perform quality assurance testing - nondestructive evaluation - of concrete pavement during placement, or soon thereafter, is desirable in order to stop placement of low quality concrete and confirm or change the mix design. Thus, laboratory experiments have been conducted to characterize the air void system in freshly placed concrete using ultrasonic guided waves. A mediator mounted onto a Plexiglas wedge is used to introduce waves from an ultrasonic transducer onto the surface of the concrete. The ultrasonic waves propagate along the surface of the concrete as Rayleigh waves. The test setup uses identical transducers, Plexiglas wedges, and steel mediators as actuators and sensors in a pitch-catch mode of operation. One challenge in this work is that hardened concrete containing cement, sand, and aggregate is quite attenuative. Add to that the desire to acquire data as soon as possible after concrete placement, when the concrete is still in a fresh state - starting as a liquid suspension containing particles (sand and aggregate) and solidifying over time, which makes it even more attenuative. Furthermore, the properties affecting wave propagation are evolving as the material state evolves from liquid suspension to solid to hardened solid. The focus of the experiments is twofold; measure the Rayleigh wave speed and quantify attenuation. The expectation is that the characteristics of the porosity will greatly affect attenuation and that it may be possible to correlate features of the attenuated ultrasonic signal with features descriptive of the air void system. However, attenuation measurements require accurate wave amplitudes and it was found that these amplitudes are very sensitive to the contact between the mediator tip and the concrete surface. Unfortunately, the contact surface between the mediator tip and concrete was too variable with the current test setup, which will be corrected in future work. In spite of this difficulty, the Rayleigh wave speed was determined, and found to depend not only on the time after placement (material state change), but also on the presence of porosity. Wave speeds are significantly less (10-22 per cent depending on time after placement) for concrete with approximately 5% porosity relative to concrete with 1% porosity. The experimental results will be compared with model predictions of elastic properties as a function of porosity.

7650-30, Session 3b

Shear wave velocity profiling and evaluation of liquefaction potential in northeast Arkansas using simplified equipment

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Soil liquefaction in Northeast Arkansas (NEA) is expected to result in substantial damage during seismic events. In-situ shear wave velocity (Vs) profile of the subsurface, to a depth of at least 30-meters (according to the International Building Code or IBC), is necessary for determining the "Site Class", which is subsequently used in the structural analysis of buildings, and can be used as a screening tool to evaluate the depth and thickness of potentially liquefiable soil layers.

Shear wave velocity profiles at 4 sites in Craighead County, AR were determined utilizing simplified equipment by means of a non-invasive technique. The results indicated good agreement with previous work performed by other researchers. These profiles were used to evaluate the liquefaction resistance at these sites using the simplified procedure by Seed and Idriss (Vs approach). The liquefaction resistance was also evaluated using the Standard Penetration Test (SPT approach) results from the geotechnical investigations that were conducted by others. The equipment and procedure should allow governmental agencies and engineering professional to determine the shear wave velocity profiles of the upper soil zones at relatively low cost. These profiles can aid different agencies in mapping areas of interest and assessing seismic hazard potential during planning future development or evaluating current facilities.

7650-31, Session 3b

Health monitoring of concrete piles using piezoceramic-based smart aggregates

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Concrete piles are widely used in the construction of civil infrastructures and it is important to perform the health monitoring of concrete piles for the safety purpose. In this paper, a piezoceramic-based innovative approach is proposed for the damage detection and health monitoring of concrete piles. A multi-functional piezoceramic-based transducer device, smart aggregate, is developed for the health monitoring purpose. An active-sensing network is formed by embedding the proposed smart aggregates at the pre-determined locations in the concrete piles before casting. In the proposed approach, one smart aggregate is used as an actuator to excite the desired waves and the other distributed smart aggregates are used as sensors to detect the wave responses. An energy distribution vector is formed based on the wavelet-packet analysis results of sensor signals. A damage index is formed by comparing the difference between the energy distribution vectors of the health concrete pile and the damaged concrete pile. To verify the effectiveness of the proposed approach, two concrete piles instrumented with smart aggregates are used as the testing objects. One concrete pile is intact and the other concrete pile has a man-made crack in the middle of the pile. Experimental results show that the there is difference between the energy distribution vectors of the damaged pile and that of the intact pile due to the existence of crack. The proposed method has the potential to be applied to perform automated integrity inspection for new piles and long-term health monitoring for piles in services.

7650-32, Session 3b

On-track testing of a power harvesting device for railroad track health monitoring

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A significant proportion of railroad infrastructure exists in areas which are relatively remote. Road crossings in these areas are typically marked with reflective signage but do not have warning light systems or crossing gates due to the cost of extending electrical infrastructure into these areas. Distributed sensor networks used for railroad track health monitoring applications can be useful in these areas, but the same limitation regarding electrical infrastructure exists. This motivated the development of an energy harvesting solution for remote railroad deployment. This paper describes on-track experimental testing of a mechanical device for harvesting mechanical power from passing railcar traffic, in view of supplying electrical power to warning light systems at crossings and to remote networks of sensors. The device is mounted to and spans two rail ties and transforms the vertical rail displacement into electrical energy through mechanical amplification and rectification into a PMDC generator. A prototype was tested under loaded and unloaded railcar traffic at low speeds. Stress analysis and speed scaling analysis are presented, results of the on-track tests are compared and contrasted to previous laboratory testing, discrepancies between the two are explained, and conclusions are drawn regarding suitability of the device for illuminating high-efficiency LED lights at railroad crossings and powering track-health sensor networks.

7650-33, Session 3b

Development of an impact monitoring system for petroleum pipelines

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Third party damage to petroleum pipelines is on the increase in most developing and this damage if undetected can led to huge financial losses, environmental pollution and most often loss of life as a result of explosion. In this paper, a wave propagation model with simple attenuation and dispersion coefficients built into it is used to simulate the pressure pulse that is generated and propagates along a pipeline to detect the impact and estimate its location along the pipeline. An inversion method was then used to generate the original form of the pressure pulse at the start of the event. An experimental test rig was developed to investigate the rate at which a pressure pulse attenuates as it propagates down a pipeline. Results obtained showed that it is possible to use the inversion method to estimate the magnitude of an damage and recreate the original form of the pressure pulse at the start of the event. The attenuation coefficient was determine to be 0.076063.

7650-34, Session 4a

A self-powered wireless SHM sensor node

D. Zhou, N. Kong, D. S. Ha, D. J. Inman, Virginia Polytechnic Institute and State Univ. (United States)

We developed a self-powered wireless Autonomous Structural Health Monitoring (SHM) Node (ASN-2) using a Texas Instruments MSP430 evaluation board, which employs a low-power, temperature-insensitive PZT-based impedance method. The ASN-2 eliminates a digital-to-analog-converter (DAC) for generation of an excitation signal and an analog-to-digital converter (ADC) for sensing the response, and elimination of the two converters reduces the power consumption of the ASN-2 dramatically. With an embedded temperature sensor, the ASN-2 is able to compensate the temperature dependency of a PZT patch. A cluster of ASN-2's forms a wireless sensor network. Each sensor node wakes up at a predetermined interval, e.g. once in every four hours, performs an SHM operation and reports the result to the host computer wirelessly. The power consumption of the ASN-2 during the sleep mode and the SHM operation is 0.15 mW and 18 mW, respectively. An SHM operation takes about 13 seconds and consumes 236 mJ. The average power of each sensor node is 0.16 mW under the aforementioned duty cycle.

Since the average power consumption of our ASN-2 is low, it offers a possibility of running the node with energy harvested from ambient sources. Mechanical vibrations are a commonly available ambient energy source for civil infrastructures, and we developed a power management circuit to harvest mechanical vibration energy using a piezoelectric cantilever. The circuit rectifies the AC output from a piezoelectric generator, while matching the source impedance dynamically, and generates a regulated DC output. Our system with a 50x31.8 mm2 piezoelectric cantilever generates up to 3.5 mW under 0.5g (rms) base acceleration. The energy harvesting system is integrated into the ASN-2 to make the node self-powered. Our analysis indicates that the energy harvested from typical bridge vibrations is sufficient to run our ASN-2. Details of the system design will be elaborated in the full paper, if accepted.

7650-35, Session 4a

Autonomous self-powered (ASP) structural health monitoring system

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Structural health monitoring technology is perceived as a revolutionary method of determining the integrity of structures involving the use of multidisciplinary fields including sensors, materials, system integration, signal processing and interpretation. The core of the technology is the development of self-sufficient systems for the continuous monitoring, inspection and damage detection of structures with minimal labor involvement. A major drawback of the existing technology for real-time structural health monitoring is the requirement for external electrical power input. For some applications, such as missiles or combat vehicles in the field, this factor can drastically limit the use of the technology. Having an on-board electrical power source that is independent of the vehicle power system can greatly enhance the SHM system and make it a completely self-contained system. Using the SMART layer technology as a basis, an Autonomous Self-powered (ASP) Structural Health Monitoring (SHM) system has been developed to solve the major challenge facing the transition of SHM systems into field applications. The architecture of the self-powered SHM system was first designed. There are four major components included in the SHM system: SMART Layer with sensor network, low power consumption diagnostic hardware, rechargeable battery with energy harvesting device, and host computer with supporting software. A prototype of the integrated self-powered active SHM system was built for performance and functionality testing. Results from the evaluation tests demonstrated that a fully charged battery system is capable of powering the SHM system for active scanning up to 10 hours.

7650-36, Session 4a

Mathematical model for power output from a bimorph plate: energy harvester under random vibration

S. Banerjee, Acellent Technologies, Inc. (United States)

Technological advancement in electronics has greatly reduced the power requirement is in the order of a few milliwatts. In the last six years, piezoelectric transduction mechanism has received great attention among the research community. Piezoelectric transduction mechanism is possibly the best candidate to meet this low power requirement. A correct mathematical model for energy harvesting technique is by far restricted to the vibrating cantilever beam problem with a tip mass. In many applications, piezoelectric transduction can also be used to harvest energy from ambient vibration by applying them directly on the host structures. A simple example of the host structure could be a vibrating plate. In this paper, a mathematical model is proposed for a vibrating bimorph plate used as an energy harvester. Generally ambient vibration is random in nature and hence

requires different mathematical technique to solve the problem. In this derivation Kelvin-Voigt type damping and viscous damping were considered separately in the dynamic equation. A solution mechanism is proposed for the system under random vibration. Then modal analysis is performed in a short circuit condition and solution from the transcendental equation is used to calculate the modal parameters. The backward coupling term is then calculated using the modal coefficients and the explicit equation for the power output is presented.

7650-37, Session 4b

Structural health monitoring system for a power boiler monitoring

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In the present work application of SHM system based on optical fiber sensors for a power boiler monitoring is presented. The test object was a modern fluid boiler named OFz-425 made by RAFAKO, supplied by hard coal and sludge coal. A nominal power of the test boiler is 336.3 MWt. In connection with replacement of pre-heater it was necessary to control if such refurbishment would not menace safety of the whole construction. It arose from the fact that additional openings in the main combustion chamber walls were made. For this purpose a structural health monitoring system based on interferometric SOFO® sensors was applied. The main task of the system was to locally measure a displacement of the construction, to give information about emerging threatens as well as to start programmed alarms. The obtained data (monitoring results) were permanently published on the secured website. An arrangement of the sensors was supported by FEM analysis of the whole construction made by boiler producer (RAFAKO S.A.). The SOFO sensors were installed on 12 tension members (strings) of the combustion chamber. Additional other 12 sensors were located directly on the chamber walls. Applied sensors ware used to measure the strain values in selected points. Then determined stresses were compared with design as well as calculated values. It allowed for evaluation of the inhomogeneous loads distribution and increase safety of construction during its repair.

7650-38, Session 4b

Non-destructive measurement of the steel cable force based on magnetoelastic effect

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It pays more and more importance on cable force monitoring recently, because cables are crucial components in cable structures. We propose a novel cable force measure method based on magnetoelastic effect which demonstrates that magnetic permeability in the ferromagnetic material varies with applied force. The method allows new application in non-destructive testing, i.e. monitoring the conditions of stayed cable. A magneto-mechanical model on differential permeability and force was put forward according to different invertigators, which could be seen as an equation of the relation between cable force and magnetic permeability for ferromagnetic materials. Applying this method in the force measurement of prestressed steel cable in Jiangsu Fasten Bloc. Company, the experimental results agree with theoretical predictions. They prove that the method is realizable and improves the mechanical force measurement.

7650-39, Session 4b

Development of antibacterial nanocomposite fiber based on PP/PET/ nanosilver

N. Golshan Ebrahimi, Tarbiat Modares Univ. (Iran, Islamic Republic of)

The polypropylene (PP) /polyethylene terephthalate (PET) /Nanosilver (Ag) nanocomposite fibers were prepared for the attainment of permanent antibacterial activity to common synthetic textile. The fibers were melt-spun by co-extrusion of PP/PET and PP/Ag master-batches and then fiber formation was carried out through the spinneret. Master-batches were made up of mixture of PP chips and nano-sized silver powder. The morphology and mechanical properties of PP/PET fiber were comprehensively assessed utilizing scanning electron microscopy (SEM) and tensile test experiments. Mechanical properties data have shown that the PP/PET blend fiber have a significant performance. The antibacterial activity of nano-silver in fibers was evaluated after certain contact time and calculated by percent reduction of two kinds of bacteria; Staphylococus aureus and Klebsiela pneumoniae. The antibacterial efficacy of spun fibers was not excellent when the master-batch used as the sheath. The SEM micrograph show nearly good dispersion of nanosilver particles with little aggregation in the polypropylene matrix. Likewise, the draw abilities of blend using hot and cold methods were evaluated.

7650-40, Session 5a

Chirplet-based imaging using compact piezoelectric array

P. Masson, D. Langlois Demers, N. Quaegebeur, P. Micheau, Univ. de Sherbrooke (Canada)

It is the purpose of this paper to present the implementation of a chirplet-based matching pursuit technique for imaging using high frequency bursts injected into a structure using a piezoceramic actuator and the measurement using a compact array of piezoceramic sensors, located remotely from the damage. The matching pursuit algorithm is implemented considering dispersive signals with a dictionary of chirplet-based atoms, where the parameters of each atom are the propagation distance and the mode. For a selected point in the scan area and a given mode, the matching pursuit algorithm is applied to obtain the correlation of the measured signal with a given atom for each propagation path in the array configuration. A round-robin technique is used to add the contributions of all these correlation values. Imaging of the entire area is obtained for a given mode by scanning over the selected points. Simulations are first conducted for a 1.5 mm thick aluminium plate with signals synthesized for A0 and S0 modes propagating over distances corresponding to the location of a reflection or diffusion point in an area in front of an array of measurement points. The simulations show that better localization of the reflection point is obtained with the matching pursuit algorithm, when compared with a group velocity-based, or TOF, approach. Then, the simulation results are validated experimentally using a 1.5 mm thick aluminium plate with a notch in the periphery of a hole. Bonded PZTs are used for both actuation and sensing of 1.5 and 4.5 cycles bursts at 300 kHz. Significant improvement of imaging quality is demonstrated with respect to classical imaging techniques.

7650-41, Session 5a

Acousto-elastic measurements and baseline-free assessment of bolted joints using guided waves in space structures

A. N. Zagrai, V. Gigineishvili, W. A. Kruse, New Mexico Institute of Mining and Technology (United States)

Integrity of bolted joints is critical for successful deployment and operation of space structures. Conventional structural qualification tests span for weeks if not for months inhibiting rapid launch of space systems. Recent developments in the embedded ultrasonic acousto-elastic method offer fast diagnosis of bolted joints and opportunities for locating the fault. However, in current acousto-elastic measurement procedures, a baseline representing the healthy condition of the joint is necessary. To mitigate a requirement of the baseline, a new methodology based on relative amplitude and phase measurements is developed. The approach has been validated on laboratory specimens and modifications were suggested for applications in realistic structures. The paper discusses principles of the baseline-free acousto-elastic method, its practical realization and respective advantages and

disadvantages. Comparison of baseline and baseline-free approaches is presented showing utility of the recently proposed methodology. Fundamentals of the acousto-elastic response were studies in experiments involving guided wave propagation in a thin plate under tension. The results indicate difference between acousto-elastic responses collected using sensors oriented parallel and perpendicular to the applied stress. It is suggested that this effect may be used to infer stress orientation in the sample. Practical issues related to acousto-elastic measurements in realistic complex structures are discussed, damage diagnosis algorithms are presented, and potential extensions of the acousto-elastic technique are proposed.

7650-42, Session 5a

Detection multi-debonding in honeycomb sandwich structures using a piezoelectric actuator/sensor network

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Multi-damage usually results in much more complex wave phenomena in the captured responses than mono-damage, which inherently imposes many challenges for guided wave based structural health monitoring. In the study, a multi-level monitoring strategy for skin-core debondings in honeycomb sandwich structures based on leaky guided waves is proposed with the aid of piezoelectric wafer actuator/sensor network. The key step of the proposed approach is hierarchically activating different sensor monitoring areas in the sensor network. In each sub sensor network, a correlation analysis is conducted between the baseline signals and those recorded at damaged condition to indicate the damage. The pseudo debonding image can be ruled out by examining consistency of the images in each sub area, and hence the final image can be reached for the real debonding locations.

7650-43, Session 5a

A low-power system design for Lamb wave methods

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A Lamb wave propagation method launches an elastic wave through the structure. The changes in both wave attenuation and reflection are sensed to detect and locate damages on surfaces. A self-contained Lamb wave system typically comprises of three different functional blocks: signal processing block, signal actuation block, and a signal sensing block. A signal processing block has a digital signal processing (DSP) chip or microcontroller unit (MCU). A signal actuation block typically adopts a digital-to-analog converter (DAC), in which the actuation signal in digital form is pre-stored in a memory and the DAC converts back the digital actuation signal into analog. The ADC unit samples the response signal and converts it into a digital signal for processing in digital domain.

Typical sampling rate and resolution of an ADC used for Lamb wave methods are in the order of a few MHz and 12 bits or above, respectively. An ADC with such a high sampling rate and resolution consumes large power. It also increases the complexity of the signal processing for a DSP or MCU chip, which, in turn, increases the power consumption of the signal processing block. In contrast, power consumption of a DAC is less than that of an ADC by an order of magnitude. So elimination of an ADC is highly effective for overall power reduction of a self-contained Lamb wave system.

In this paper, we present a new system design, which eliminates an ADC for Lamb wave methods. Our method is, in essence, to sense the polarity of the received signal using a specialized comparator. A comparator is functionally equivalent to a one-bit ADC, and so the circuit complexity of a comparator is much simpler than that of a typical ADC used for Lamb wave methods. So adoption of a comparator itself significantly reduces the power consumption. Further, it drastically simplifies the complexity of the signal processing, which, in turn, reduces the power dissipation of a DSP or MCU chip. We present details of our method including power saving and system performance in the full paper.

7650-44, Session 5b

Missile captive carry monitoring using a capacitive MEMS accelerometer

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Military missiles are exposed to many sources of mechanical vibration that can affect system reliability, safety, and mission effectiveness. One of the most significant exposures to vibration occurs when the missile is being carried by an aviation platform, which is a condition known as captive carry. If the duration of captive carry exposure could be recorded during the missile's service life, several advantages could be realized. Missiles that have been exposed to durations outside the design envelop could be flagged or screened for maintenance or inspection; lightly exposed missiles could be selected for critical mission applications; and missile allocation to missions could be based on prior use to avoid overuse. The Army Aviation and Missile Research and Development and Engineering Center (AMRDEC) has been developing health monitoring systems to assess and improve reliability of the missiles during storage and field exposures. Under the direction of AMRDEC staff, engineers at the Pacific Northwest National Laboratory have developed a Captive Carry Health Monitor (CCHM) for the Hellfire missile. The CCHM is a usage monitoring device installed on the outer skin of the Hellfire missile to record the cumulative hours the host missile has been in captive carry mode and thereby assess the overall health of the missile. This paper provides an overview of the CCHM electrical and package design, describes field testing and data analysis techniques used to identify captive carry, discusses the application of probabilistic engineering methods to analyze the data and predict component reliability, and discusses the potential application of missile health and usage data for real-time reliability analysis and fleet management.

7650-45, Session 5b

Propulsion health monitoring of a turbine engine disk using spin test data

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On line detection techniques to monitor the health of rotating engine components is becoming increasingly an attractive option to aircraft engine companies to increase safety of operation and lower maintenance costs. Health monitoring remains a challenging feature to easily implement especially in the presence of scattered loading conditions, crack size, component geometry and materials property. The current trend, however, is to utilize noninvasive types of health monitoring or nondestructive techniques to detect hidden flaws and mini cracks before any catastrophic event occurs. These techniques go further to evaluate materials' discontinuities and other anomalies that have grown to the level of critical defects that can lead to failure. Generally, health monitoring is highly dependent on sensor systems that are capable of performing in various engine environmental conditions and able to transmit a signal upon a predetermined crack length, while acting in a neutral form upon the overall performance of the engine system. Efforts are under way at NASA Glenn Research Center through support of the Intelligent Vehicle Health Management Project (IVHM) to develop and implement such sensor technology for a wide variety of applications [1-5]. These efforts are focused on developing high temperature, wireless, low cost and durable products.

Therefore, in an effort to address the technical issues concerning health monitoring of a rotor disk, this paper considers data collected from an experimental study using high frequency capacitive sensor technology to capture blade tip clearance and tip timing measurements in a rotating engine-like-disk-to predict the disk faults and assess its structural integrity. The experimental results collected at a range of rotational speeds from tests conducted at the NASA Glenn Research Center's Rotordynamics Laboratory, a high precision spin rig, will be evaluated using multiple data-driven anomaly detection techniques

[6-9] to identify anomalies in the disk. This study is expected to present a select evaluation of online health monitoring of a rotating disk using these high caliber sensors and test the capability of the in-house spin system.

References

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7650-46, Session 5b

Positioning challenges in reconfigurable semi-autonomous robotic NDE inspection

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As part of the UK Research Centre for Non Destructive Evaluation (RCNDE), The University of Strathclyde has undertaken research into the potential of miniature semi-autonomous wireless inspection vehicles to deliver a variety of NDE inspection techniques to structures in challenging inspection areas (for example oil, gas, and nuclear). The inspection vehicles can incorporate a number of different NDE payloads including ultrasonic, eddy current, visual and magnetic based payloads, and have been developed over the last six years into an adaptable and flexible inspection platform. However a significant challenge remains in the accurate positioning and guidance of such vehicles for real inspection tasks. Employing both relative and absolute position measurements, we discuss a number of solutions to position estimation from conventional Kalman filtering to more sophisticated probabilistic approaches based on a particle filter approach. Central to the success of this approach is the ability to consider the positioning problem under the same mathematical framework used for the fusion of data from a variety of different NDE sensors. In this fashion the uncertainties in both position and defect identification and classification are dealt with using a consistent approach. A number of practical constraints and considerations to different precision positioning techniques are discussed, along with NDE applications and the potential for improved inspection capabilities by utilising the inherent reconfigurable capabilities of the inspection vehicles.

7650-47, Session 5b

An integrated health management system for real-time impact monitoring and prediction of impact-induced damage on composite structures

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Next generation technology of integrated health management systems for air-transportation structures will utilize SHM methods in combination with simulation techniques for the prediction of structural degradation induced by adverse events such as impacts. The contribution focuses on the development of an advanced real-time monitoring system for impact loads using passive sensing networks. Starting from the fundamental approach of real-time monitoring based on system identification models, problems of model order, signal conditioning and efficient model training will be addressed. In addition, the proposed system includes novel techniques that provide an efficient system calibration. These techniques are aimed to avoid extensive testing during the calibration process which might be difficult, timeconsuming, and expensive for large-scale structures. The measurement of performance of the impact monitoring system using probability and accuracy of detection (POD) will be supplied by either results from numerical simulation or experimental data. Finally, the load monitoring system is interactively linked to a damage prediction module based on numerical failure analysis employing composite failure criteria. The utilization of appropriate database techniques allow a real-time prediction of impact induced damage after detection of any adverse impact event by the passive sensing system making information available on developing degradation at the earliest possible state.

7650-48, Session 6a

Efficient finite element modeling of scattering for 2D, 3D and guided waves problems

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The scattering of waves by defects is central to ultrasonic NDE and SHM. General scattering problems must be modeled using direct numerical methods such as finite elements (FE). The execution of such models is very computationally demanding. At last year's meeting, the basis of a computationally efficient technique for predicting scattering behavior using a commercial FE package was presented. The concept is to only model the scatterer itself and a minimal region of the surrounding host medium. An encircling array of monopole and dipole sources is used to inject an arbitrary wavefront onto the scatterer. The scattered field is monitored by a second array of monitoring points, outside the excitation array, and using Huygen's principle, this can be projected to determine the scattered field at any point in space. In practice, the incident wave is chosen to be a plane wave incident from a given angle and the scattered field is projected to distant points in the far-field of the scatterer. This enables direct synthesis of the far-field scattering or S-matrix of a defect, which encodes all the available scattering information. Since presenting the concept of the method at last year's meeting for 2D scattering, the technique has been refined and generalized to include 3D and guided wave scattering problems in both isotropic and anisotropic media. Refinements include the ability to use a free mesh of 2D triangular or 3D tetrahedral elements in the FE model, and the removal of the requirement to run reference 'defect-free' models.

7650-49, Session 6a

Frequency-domain bridging multiscale method for wave propagation simulations in damaged structures

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Efficient wave propagation models are extremely important to simulate the interaction of propagating waves with localized defects. Such models enable the development of novel damage detection algorithms and are useful to support the interpretation of experimental measurements. Classical finite element models may be computationally time consuming, especially when detailed models are essential to capture the interaction of propagating waves with defects. Moreover, if a refined mesh is limited to the discontinuity region, spurious reflective waves may be generated. The elimination of these spurious waves can be achieved by means of a multi-scale approach where a localized fine-scale mesh is coupled with a coarse-scale discretization using proper dynamic interface conditions according to the bridging scales method. A frequency-domain formulation of the bridging multiscale method is implemented in order to further reduce the computational cost. Numerical results are presented for propagating elastic waves in 1D and 2D damaged structures based on spectral element approximations of the wavefield.

This approach combines the flexibility of finite element techniques in dealing with irregular geometries, with the high accuracy of spectral element methods.

Within this framework, a frequency-based bridging method seems a promising tool to model small discontinuities while the spectral method ensures

highly-accurate results also for a coarse discretization of the computational domain. Wave propagation results for a mechanical input show main wave reflections in the refined zone due to the induced damage. Also it is possible to observe that the wavefield is free from spurious reflections arising from the interface of the two regions. Snapshots of the response illustrate the good overlapping of the coarse-scale and refined solution.

7650-50, Session 6a

Transient ultrasonic wave field modeling in an elastic half-space using distributed point source method

S. Das, S. Banerjee, Acellent Technologies, Inc. (United States); T. Kundu, The Univ. of Arizona (United States)

Transient ultrasonic waves in an elastic half-space generated by an ultrasonic transducer of finite size are modeled by the Distributed Point Source Method (DPSM). DPSM which is a Green's function based semi-analytical mesh-free technique is modified to incorporate the transient loading from a finite size acoustic transducer. Fast Fourier transform (FFT) of the transient loading is computed and then DPSM is used to compute the ultrasonic field at different frequencies and then inverse fast Fourier transform (IFFT) is taken to get the transient response of an elastic half-space excited by a bounded acoustic beam. Numerical results are generated for elastic half-space excited with normal incidence of acoustic beam. Then the transient Rayleigh wave in the solid half-space is generated. The modeling is then extended to the transient response of an elastic half-space containing a crack, struck by a bounded acoustic beam. It is discussed in the paper what type of useful information that is hidden in the steady state solution can be obtained from the transient results.

7650-51, Session 6a

Modeling and characterization of micro-fiber composite rosettes for lamb wave excitation

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The paper describes a numerical technique for the analysis of Lamb Wave generation in plate structures using Macro-Fiber Composite (MFC) piezoelectric rosettes. The considered technique is formulated in the frequency/wavenumber domain, where a solution for the propagating waves is sought in terms of the spatial Fourier Transform (FT) of the stress field applied by each MFC patch. The estimation of such a field relies on the numerical analysis of the patch-plate interaction evaluated through a detailed Finite Element (FE) model. The frequency domain solution from the detailed model is used to estimate the wavenumber content of the excitation, which is subsequently fed to the analytical procedure for the evaluation of the far-field harmonic response of the plate. The response in the spatial and temporal domains is finally obtained through the numerical computation of inverse FTs operating both on the wavenumber and frequency contents of the response. This semi-analytical approach allows the efficient simulation of Lamb wave propagation in plate structures, while accounting for complex actuation configurations and bonding layer effects.

The technique is first tested on simple piezoelectric shape structures to validate its accuracy and subsequently applied to MFC patches of different polarization. Actuation directionality is specifically investigated for a single MFC patch and for multiple MFC patches mounted in rosette configurations. The predicted directionality is compared with experimental measurements obtained with a scanning laser doppler vibrometer. The experimentally detected wavefield data are represented in the wavenumber domain through the application of two-dimensional FTs, where the variation of the response amplitude in terms of the propagation direction is conveniently estimated.

7650-52, Session 6a

Efficient methods to model the scattering of ultrasonic guided waves in 3D

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The propagation of ultrasonic guided waves and their interaction with a singularity is of interest to the non destructive testing community. There is no general solution to the scattering problem and it is still an ongoing research topic. Due to the complexity of guided wave scattering problems, most existing models are related to the 2D case. However, thanks to the increase in computer calculation power, specific 3D problems can also be studied, with the help of numerical or semi-analytical methods. This paper is an overview of three efficient methods aimed at modeling 3D scattering problems. The first method is the use of the Huygens principle to reduce the size of finite element models. This principle allows the area of interest to be restricted to the very near field of the defect, for both the generation of the incident field and the modal decomposition of the scattered field. The second method consists of separating the 3D problem into two 2D problems for which the solutions are calculated and used to approximate the 3D solution. This can be used at low frequency-thickness products, where Lamb waves have a similar behavior to bulk waves. The last method is a semi-analytical approach to the 3D scattering of guided waves by a flat bottom hole of arbitrary curved shape. This allows modeling scatterers such as circular and elliptical holes or cracks. These three methods are presented briefly and compared on simple scattering cases.

7650-53, Session 6b

Fatigue damage assessment using high frequency resonance measurements

W. A. Kruse, A. N. Zagrai, V. Gigineishvili, New Mexico Institute of Mining and Technology (United States)

Dynamic measurements are widely used for structural condition assessment and damage detection. A wide range of studies are available on vibration-based detection and identification of fatigue cracks in simple and complex structures. This research explores the application of the electromechanical impedance method and nonlinear resonance measurements to high frequency detection of incipient fatigue damage in aluminum alloy specimens. The electromechanical impedance method relies on the coupling between the mechanical properties of a structure and the electrical properties of attached piezoelectric wafer active sensors (PWAS). This coupling allows structural properties to be inferred from the electrical impedance signature of the sensor. In this study, the electromechanical impedance method is utilized for assessment of material deterioration under cyclic fatigue loads. Aluminum specimens were subjected to increasing fatigue cycles at stress amplitudes below the yield point, and electromechanical impedance signatures were taken at discrete levels of fatigue damage. Linear and nonlinear features of the impedance signatures were compared for different damage conditions. The results show a downward frequency shift of impedance peaks with increasing fatigue load. This frequency shift is observed before visible crack development and fracture. Nonlinear resonance tests were applied to fatigued aluminum samples. PWAS were utilized for transmission and reception of elastic waves at increasing amplitude levels. Variations in structural dynamic characteristics were considered for different excitation conditions and increasing damage severity. This paper discusses damage detection capabilities of each method and provides perspectives for utilizing information on incipient damage for predicting structural performance under known operational loads.

7650-54, Session 6b

Gaussian mixture regression for fatigue damage monitoring

S. Banerjee, X. P. Qing, S. J. Beard, Acellent Technologies, Inc. (United States)

In this paper Gaussian Mixture Regression technique is used to monitor structural components that are under severe fatigue loading. Mechanical loading in association with thermal loading in many aircraft components are vulnerable to the structural integrity. Hence an early detection mechanism should be developed. With the present technology of Structural Health Monitoring (SHM) abandon data can be collected or can be generated in real time. But processing of the data and coming up with correct interpretation of the data, is still a challenging task. Because most of the interpretation techniques rely on baseline data set that are collected from the component. Although several baseline free techniques are proposed, their real world application is far fetched. Hence, a technique in between the existing solutions is necessary for immediate use. Gaussian Mixture Model (GMM) for Hot Spot monitoring proposed by Banerjee, et.al has been proved to be effective way to generate early alarm system. However, this technique requires large number of statistical data set, which is sometimes impractical to collect. Using the proposed technique (GMR) representative statistical data set can be generated for any component and can be used as priori data for any component. GMR and GMM together could develop a best solution for damage estimation in metal and composite components that are under fatigue loading.

7650-55, Session 6b

Magneto elastic active sensors for structural health monitoring using magneto-mechanical impedance and elastic wave propagation

T. A. Barnes, D. Kukhalashvili, A. N. Zagrai, New Mexico Institute of Mining and Technology (United States)

Magneto-elastic active sensors (MEAS) offer an alternative to piezoelectric wafer active sensors (PWAS) for structural health monitoring (SHM) applications. In essence, a MEAS consists of a coil of wire carrying a time-varying electrical current in the presence of a static magnetic field. The Lorentz-force mechanism facilitates transduction without a mechanical bond between the sensor and the host structure, thereby circumventing some of the shortcomings of PWAS. In this paper, the development of MEAS is briefly recounted and applications of MEAS to SHM are presented. The miniaturization of MEAS for improved embeddability is also discussed. The ability of MEAS to detect loose bolts by the pitch-catch method is presented; results indicate that signal amplitude and phase change with bolt condition. MEAS application for near-field and far-field crack detection is also explored. Finally, the utilization of MEAS in Magneto-Mechanical Impedance (MMI) method is discussed. The MMI technique provides a means of assessing the integrity of metallic structures through measurement of structural dynamic response. Since structural damage affects mechanical properties, it modifies structural dynamic characteristics reflected in MMI signature. The use of MMI to monitor fatigue damage in aluminum alloys is presented. Aluminum samples were subjected to cyclic loading in increments of 10,000 cycles until cracks appeared. The MMI responses show downward frequency shift of impedance peaks as samples deteriorate under fatigue loading, confirming the capability of MMI techniques to detect incipient fatigue damage. Thus, the applicability of MEAS to various SHM techniques is demonstrated, and the advantages and disadvantages of MEAS are explored.

7650-56, Session 6b

Influence of guided ultrasonic wave scattering directionality on the detection sensitivity for SHM of fatigue cracks

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Localized and distributed guided ultrasonic waves array systems offer an efficient way for the long-term monitoring of the structural integrity for large structures. The use of permanently attached sensor arrays has been shown to be applicable to detect simulated corrosion damage. However, the detection sensitivity for fatigue cracks depends on the location and orientation of the crack relative to the transducer elements. Crack-like defects have a directionality pattern of the scattered field depending on the angle of the incident wave relative to the defect orientation and on the ratio of the characteristic defect size to wavelength. From FE simulations it has been shown that for cracks and notches almost no energy is scattered in certain directions from the defect, i.e., the data processing algorithm must take into account that for some transducer combinations no change in the signal even for a significant defect will be detected. The directionality pattern of the scattered field for the A0 Lamb wave mode is predicted from 3D Finite Element simulations and verified from experimental measurements at machined part-through and through-thickness notches using a laser interferometer. Good agreement is found and the directionality pattern can be predicted accurately. The amplitude of the scattered wave is quantified for a variation of angle of the incident wave relative to the defect orientation, the defect depth, and the ratio of the characteristic defect size to wavelength. These results provide the basis for the quantification of the detection sensitivity for defects in plate structures using guided wave sensors.

7650-57, Session 6b

Comparison between different damage estimation techniques for monitoring fatigue damage in terms of computation power requirement

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Fatigue crack detection and quantification is by far the most challenging task in Structural Health Monitoring (SHM). In the past decade numerous techniques were developed to detect and quantify the fatigue damage. Fatigue damage could include fatigue cracks in metals, delamination growth in composite structure etc. It has been found that different techniques are suitable for different problems. Hence, selection of right analysis methodologies pertaining to different problems is crucial. On the other hand power requirement to drive the electronics is reducing day by day which is motivating the researchers to develop elegant energy harvesting technologies. But current power output is not sufficient to perform both the structural scan and analysis of data. Hence, when there is a need to enhance the power output from the energy harvesters, we also need to reduce the power requirement for data analysis. This requirement drives the idea of developing low power damage detection algorithms. In this paper a comparison between few most popular techniques are presented. Different problems with different materials and different structural geometries are considered. Although, all possible and existing techniques (including vibration based analysis) are enumerated in the paper, three techniques were down selected and analyses are performed. A comparison on their time requirement to perform analysis using standard computing system is also presented.

7650-58, Session 7a

Magnetostrictive sleeve transducer for in-situ monitoring of specimens

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In the literature, there are several examples where wires of magnetostrictive material are used for both sensing and nondestructive inspection applications. However, the magnetostrictive material may not be suitable for certain environments (such as corrosive environments). Therefore, designs where the magnetostrictive material is coupled to a more robust waveguide material are of interest. The work presented in this paper examines a design based on a cylindrical sleeve of magnetostrictive material. Experiments were conducted to compare the new sleeve design to the old approach of using a brass coupling. In addition to simplifying the manufacturing process, the sleeve design was found to eliminate signal artifacts encountered in previous results.

7650-59, Session 7a

Development of a novel polymeric fiber-optic magnetostrictive metal detector

W. Wang, Univ. of Washington (United States)

Metal detectors are used extensively especially in the areas of defense, security and environmental applications. Modern metal detectors operate on three basic technologies: Very low frequency (VLF), Pulse induction (PI), Beat-frequency oscillation (BFO).

Theses sensors appear as a walk-through or hand held configuration and are commonly seen at the airport, library, prison, stores and shops. These devices however are relatively large, and are highly affected by the surrounding electronics and vice versa due to its RF operation. If applications are to be used in the hospital or laboratory where limited spaces are available and equipments are prompt to electromagnetic interference, these detectors will not work well in the environment. In this paper, we present a compact metal detector that can resolve these problems. The detector uses a newly developed polymeric fiber-optic Mach-Zhnder magnetostrictive sensor. The detector utilizes a simple DC magnetic field detection scheme and a Mach-Zhnder fiber optic interferometer for metal detection. The basic concept of the metal detection is based on monitoring strain-induced optical path length change in the interferometer stems from the magnetic field induces magnetostriction effect. The magnetostrictive device can produce polarized magnetic fields that have temporal characteristics such as generated from walk-through metal detectors. Based on the fact that different metal targets have different magnetic disturbances, different metal objects can be indentified. This fiber-optic magnetostrictive metal detector is much less complex, relatively smaller in size, and easy to fabrication. In addition, this technique is free from RF interference. In this paper, the theory, design and preliminary results on the metal detection are presented.

7650-60, Session 7a

Towards a nanofilm-coated photonic crystal fiber long-period grating refractive index sensor: corrosion detection for structural health monitoring

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The array of axially aligned air channels and the robust waveguide characteristics of silica photonic crystal fibers (PCFs) integrated with long-period gratings (LPGs) make them a powerful platform for chemical sensing and detection. Due to the fact that the structural health monitoring plays an important role in the observation deformation and environmentally-induced degradation in buildings, tunnels, bridges, and other civil infrastructures, we are, in this work, exploring the possibility for using nanofilm-coated PCF-LPGs as corrosion sensing devices that present new opportunities for evanescent wave detection with enhanced sensitivity (resonant wavelength shift ~ 1pm/10-7 RIU) and selectivity (in terms of identifying corrosion species). We first present the simulation of mode properties of selected PCF-LPG for optimization of mode filed distribution, light power overlap, and confinement loss. The numerical calculation reveals that if the optimized cladding mode can be selectively excited and coupled by an LPG, it would fundamentally transform the conventional approach to evanescent filed sensing using PCF-LPG transducer. We then fabricate LPGs in index-guided PCF by stress relaxation utilizing CO2 laser irradiation with scanning capability. We finally deposit nanoscale overlays on the surfaces of air channels in cladding of PCF-LPG for analyte absorption by employing the electrostatic self-assembly (EAS) layer-by-layer technique. The resultant PCF-LPG sensor can provide sub-ppm detection of water moisture at room temperature. The advantages of proposed nanofilm-coated PCF-LPG sensors are that they can be integrated within the protective cover (such as wrapping wire, paint or polymer/mortar mix) that is used to prevent moisture ingression, and they can be integrated into newly-built cable structures or when corroded cables are replaced in existing cable-stayed bridges, and they can also be tailored to detect moisture as well as some corrosion products.

7650-61, Session 7a

A MEMS based measurement system for structure health monitoring applications

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The structure health monitoring becomes more and more important to increase the reliability of important assemblies and structures. But also the preventive failure analysis is a very important point to assure a high reliability even if components are changed not anymore by rotation but only as required. This is much more economic but it assumed a perfect working sensor system for structure monitoring.

Therefore, a silicon test chip was developed to analyse acting mechanical loads at critical structure locations. Standard MEMS technologies are used for manufacturing an array structure of stress sensitive elements. For low expected loads measurement cells with diaphragms are used which are realized by anisotropic etching with potassium hydroxide. These diaphragms generate a stress step-up and act as mechanical amplifier. Other test chip types are designed for higher loads without diaphragm and are modular composed of single measurement cells which results in variable chip size which can be realized. Therefore, an adaptation on special application situations is possible. For stress detection and as electrical mechanical converter piezo resistive solid state resistors are utilized. These resistors are realized by local boron diffusion into the silicon substrate. Liquid spin-on-dopand which contains a borosilicate polymer act as diffusion source. For contacting and wiring a metallization layer is generated which prepare all necessary contact pads for a 4-terminal sensing of the resistors.

The measurement hardware is developed at our institute, too. It is a high integrated and full programmable circuit for the autonomous data collection and storage. The hardware is composed of an analog circuit for multiplexing and digitizing of the different measurement channels, and a digital circuit for logic control and forming of digital interfaces like Ethernet, USB or flash memory. Up to 16 sections with each 6 resistors can be measured continuously. Hence, overall 96 resistors can be monitored by one unit.

The measured and stored raw data can be transferred to a computer. A proper software was written to eliminate all systematic errors the temperature depending of the piezo resistive coefficient.

Another point is the interpretation and visualization of the measured resistance values of the piezo resistors. Each the combination of two resistors results to a value of mechanical stress. In this way the corrected data in the form of mechanical stress values are given to the user or can be logged automatically for a long term structure monitoring.

The whole system can be utilized as a self-sufficient measurement chain for structure health monitoring. The application of MEMS technology is an economic way to get small, lightweighted and reliable sensor elements for detecting mechanical loads. Due to all these features and the modular character this system can be easily integrated into an existing bus system of automotive vehicles. Furthermore, due to the ability of scaling the measurement cells a wide field of monitoring situations are feasible. Starting with PCBs ranging to load-bearing joints.

7650-62, Session 7a

Development of a polymeric capacitive 3-D tactile sensor

W. Wang, Univ. of Washington (United States)

In this paper, we present a novel polymeric 3-D tactile sensor. The tactile sensor comprises a flexible quad capacitor array where three axial forces can be measured from the sensors' relative areas and gap distances changes using a simple differential equation. To improve the overall performance of the sensor, several high dielectric polymers were developed so that a smaller sensor area (< 1x1mm2) can be achieved. A specially designed RF circuit was also developed to improve the capacitance detection. With current configuration, sensor is capable of detecting forces in any arbitrary direction with a sensitive of 0.1mN and a force range up to 10N.

7650-63, Session 7a

Surface acoustic wave generation and detection by Coulomb excitation

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Piezoelectric excitation and detection on crystal surface is caused by a gradient in the piezoelectric properties respectively a gradient in the electric field in piezoelectric materials. The relatively weak coupling is usually enhanced for established practical applications by mechanical, geometrical and electrical resonances. The geometrical resonances as present for the commonly used inter digital transducer (IDT) lead to limitations concerning the spatial and temporal resolution that can be achieved with such devices. Concentration of the electric field by geometrical means and point like conversion at the surface of piezoelectric materials is the basis for the novel scheme presented here. The principles of the developed method together with instrumental details are discussed. Applications involving two dimensional imaging with time resolved recording for each pixel of the image for phase and magnitude of the transfer and echo signals are presented. Comparison of the experimental data with model calculations for the expected anisotropic transport in piezoelectric crystals and applications concerning microscopic tomographic imaging by the developed methods are presented and discussed.

7650-64, Session 7a

Structural health monitoring of composite structures by carbon nanotubes and piezoelectric sensors

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The fatigue life and damage tolerance of composite structures are strongly affected by matrix cracks between fibers as microcracks or between layers as ply delamination. An integrated system of carbon nanotubes and piezoelectric sensors is developed for structural health monitoring (SHM) of composite structures. The hybrid system is designed to detect both microcracks and localized damage/delamination in composite structures. It combines the unique sensing capabilities of carbon nanotubes along with those of a piezoelectric sensor network to sense the location, nature and extent of damage. In order to localize the detected damage using the carbon nanotube sensors, a thin dielectric film (SMART Layer) with distributed electrodes is developed. The distributed electrodes on the SMART Layer are utilized to measure the conductivity of the carbon nanotube networks at different locations across the structure. Localized damages in the structure are measured by the conductivity changes from the electrically conductive carbon nanotube networks formed inside the polymer matrix. Additionally, the SMART Layer will include an embedded network of piezoelectric actuators/sensors to detect/verify the localized cracks and delaminations. The integrated hybrid nanotube/piezoelectric SHM system is able to detect initiation of damage and monitor its growth.

7650-65, Session 7b

Structural health monitoring of helicopter hard landing using 3D digital image correlation

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During operation of vehicles and structures, excessive transient loading can lead to reduced fatigue life and even mechanical failure. It has been shown that when a structure undergoes a damaging sequence of events, such as those witnessed during a helicopter hard landing; the structural health of the specimen can be severely affected. Traditional sensors have drawbacks, such as providing only local information about the health of the structure, and causing mass loading or local stiffness changes. In order to quantify this damage and monitor the structural health of the specimen, experimental data is required across a wide area of the helicopter.

Within this paper the use of three-dimensional digital image correlation (3D DIC) is examined as a possible method to acquire the necessary data to perform structural health monitoring in a non-obtrusive manner. 3D DIC is a non-contacting measurement technique that utilizes a stereo pair of digital cameras to track prescribed optical targets placed on the structure. The approach can provide global information about changes to the structure over the entire field of view. A scale laboratory test is performed to simulate a helicopter hard landing. The changes in the structural shape and strain field of the model helicopter fuselage as a direct result of the hard landing are identified. The tests demonstrate that this technique is a valid way to determine the damage inflicted on a structure due to an excessive applied loading or a dynamic maneuver. Practical applications and common limitations of the technique are discussed.

7650-66, Session 7b

Characterization of acoustic lenses with the Foucault test by confocal laser scanning microscopy

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In this work, the Foucault knife-edge test, which has traditionally been known as the classic optical test for optical imaging devices, is used to characterize an acoustic lens for operation at 1.2 GHz. A confocal laser scanning microscope (CLSM) was used as the illumination and detection device utilizing its pinhole instead of the classical knife edge that is normally employed in the Focault test. Information about the geometrical characters, such as the half opening angle of the acoustic lens were determined as well as the focusing properties of the lens. The smallest focal spot size that could be achieved by the examined lens restricted by geometrical limitations was found to be about 1 µm.

7650-67, Session 7b

Paired structured light configuration for structural health monitoring

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The displacement measurement in structural health monitoring (SHM) was not popular due to inaccessibility and the huge size of the civil infrastructures. The frequently employed approaches such as accelerometer, strain gauge, PZT, GPS, LVDT(Linear Variable Differential Transformer) require high cost and are difficult to install and maintain. To develop an SHM system that directly measures the displacement of the structure using low-cost sensor, we proposed a multiple paired structured light (SL) system. The proposed paired SL module which uses two lasers and a camera in pair is inexpensive to implement and can directly measure the accurate relative displacement between any two locations on the structure. Based on various simulations, a minimal configuration of the paired SL module was found. And the steepest descent and extended Kalman filter-based displacement estimation methods was proposed by deriving a kinematic equation and its constraints.

In this paper, we theoretically justify the minimal configuration of the proposed paired structured light system. To do so, another configuration such as four lasers in only one side is further investigated. The calibration method used in stereo vision can be applied in this specific configuration. After performing simulations using various configurations, the performances among them are analyzed and compared. After building a prototype of the paired SL module, some

real experiments are performed to test the feasibility of the system for a structural displacement monitoring.

7650-68, Session 7b

Hardware complexity for extrinsic Fabry-Perot interferometer sensor processing

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A number of Extrinsic Fabry-Perot Interferometer processing techniques have been demonstrated for use to extract gauge-length measurements from optical detector output signals. These include: (1) the artificial Neural Network method, (2) the acos method, (3) the iterative search method, and (4) the spectral combination method. For applications where the processing is to be performed with low-power hardware co-located with the sensor, the hardware implementation architecture and complexity become critical for a practical solution. In this paper, implementation complexity tradeoffs and comparisons are given for various implementation architectures for each method with respect to each gauge-length estimate. Our research considers complexity as measured in terms of the number of hardware-resident arithmetic operators, the total number of arithmetic operations performed, the data memory size, and the critical execution path. It is shown that accurate gauge-length estimates are achievable with implementation architectures suitable for applications including low-power implementations and high-power scalable implementations.

7650-69, Session 7b

Optical encoder feedback system for levitating three phase rotor system

W. Wang, Univ. of Washington (United States)

This paper described the design and fabrication of a three phase motor using a diamagnetically levitating rotor system. The planar rotor described in this paper uses a triangular configuration of magnets that rotates by nine electric coils evenly spaced around the rotor. A optomechanical feedback control system was created in order to control the frequency at which the rotor would spin. The prototype was controlled by a mechanical relay circuit which latched based on a DC pulse signal run by a control algorithm. The mechanical relay circuit allowed a current to the rotor coils (the actuators of this system), which then produced an electromagnetic field strong enough to spin the rotor. Several different input waveforms were tested to optimize the spinning speed of the rotor. A phase advancement control algorithm is also created to help correct the frequency and phase errors so that a desired rotor speed is maintained.

7650-70, Session 7b

Acousto-shearographic method for detecting adherence anomalies

O. Giraudo, ONERA (France)

Foam on metal is often used in aeronautic. Despite the fact that high performance bonding processes are already available, there is no a priori insurance in the bonding quality. So the need for testing is high because the adhesion is critical for some mission. For small structures there is no real problem, as good NDT methods are existing. But, at large scale, not only the quality of the control but also the productivity of the testing process must be relevant. Such a constraint has been taken into account, at Onera, in developing a tool which can be used in industrial environment.

The principle lies on the benefit that might come from using two physical disciplines : optics for reading the target phenomena, acoustics for its stimulation. The method is derived from an optical interferometric technic which, after some adaptation, has become suitable for detecting surface acoustical waves. These waves, classical Lamb ones, propagate through the foam layer by a proper choice of the coupling parameters and test the mechanical conditions existing at the interface. Shearography is then used for imaging the waves.

The next step was to define a way to process the numerical results, and find a suitable algorithm in order to carry out the detection of the defaults. The developing solution led to a sensitive and robust method, giving a simple visual diagnostic with particularly convincing results. Moreover, from an operational point of view, and compared to solutions which are essentially local, the system developed offers a good productivity as results appear as figures of contrast. First tested on plane samples, the system has recently given good results on complex ones.

7650-119, Poster Session

A no-calorimetric method for measuring SAR in MRI

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During an MRI procedure, the patient absorbs a portion of the transmitted RF energy, which may result in tissue heating and other adverse effects, such as alterations in visual, auditory and neural functions.

The Specific Absorption Rate (SAR), in W/kg, is the RF power absorbed per unit mass of tissue and is one of the most important parameters related with thermal effects and acts as a guideline for MRI safety. In fact, strict limits to the SAR levels are imposed by patient safety international regulations (CEI - EN60601 - 2 - 33) and SAR measurements are required in order to verify its respect. SAR value depends on different factors, such as the induced electric field, the pulse duty cycle, the tissue density, permittivity and conductivity.

SAR estimation in Magnetic Resonance scanners can be conducted both numerically and experimentally. In the former case, SAR is estimated theoretically by numerical solution of the Maxwell equations and the induced field determination based on field source and human body models. In the last case, the induced field by real source is estimated directly in experimental phantoms having dielectric properties similar to the human body. In the experimental approach, the used sensors can be either electric field sensors or temperature sensors. Present used approaches and methods have some important limits: the numerical approach is not easy to use in modeling field sources, above all with the most recent used pulse sequences. The possibility of measuring the absorbed power, as a difference between the pulse power produced by the scanner and the reflected power, requires the use of electronic instruments that should be connected to the scanner coils. That operation would require the presence and collaboration of the scanner producer technicians and in this manner the method is not so easily feasible as well as not much sensitive.

In the experimental approach, the most promising techniques are those relative to temperature sensors, because they refer directly to dielectric, conductivity and thermal properties of the human body. Simpler are the calorimetric methods, also if in this case long acquisition times are required in order to have significant temperature variations and accurate heat capacity knowledge. In this method, it is necessary to reduce thermal losses by a totally adiabatic phantom. Furthermore, long measurement times (1 hour and a 1W/kg SAR is required to have a temperature increase of 0.86 C) and compatible magnetic field thermometer are required.

In this approach, however, a perfect adiabatic phantom and accurate heat capacity knowledge are required.

The phase transition method, here proposed, is a new method to measure mean SAR in MRI which has the advantages to be very simple and to overcome all the typical calorimetric method problems. In fact, it does not require any in gantry temperature measurement and any specific heat or heat capacity knowledge, but only simple mass and time measurements. For its simplicity, it can be used in order to verify the respect of SAR limits without the presence and collaboration of any scanner producer technicians and without long operational stops.

7650-120, Poster Session

MATCAKE, a flexible toolbox for 2D NMR spectra integration by CAKE algorithm

R. Romano, F. Acernese, Univ. degli Studi di Salerno (Italy); A. Motta, D. Paris, F. Barone, Istituto Nazionale di Fisica Nucleare (Italy)

MatCAKE (cake.unisa.it) is a toolbox for integrating 2D NMR spectra by the CAKE (Monte CArlo peaK volume Estimation) [1] algorithm within the Matlab environment (www.mathworks.com).

Quantitative information from multidimensional NMR experiments can be obtained by peak volume integration. The standard procedure (selection of a region around the chosen peak and addition of all values) is often biased by poor peak definition because of peak overlap. CAKE is a simple algorithm designed for volume integration of overlapping peaks.

Methods

Assuming the axial symmetry of two-dimensional NMR peaks, as it occurs in NOESY and TOCSY when Lorentz-Gauss transformation of the signals is carried out, CAKE estimates the peak volume by multiplying a fractional peak volume by an R factor, which is a proportionality ratio between the total and the fractional peak volume, both evaluated with Monte Carlo techniques.

Results and Conclusions

Integration of simulated and experimental 2D in-phase peaks with different degree of overlap shows that CAKE works well even for strongly overlapping peaks. The main advantage of CAKE is its simplicity as difficulties in its use are comparable to those presented by methods that sum all data points in a defined area. In fact, the user only has to select a peak slice not overlapping with other peaks therefore avoiding the guess of the total contour shape of the peak. Furthermore, CAKE does not require any time-consuming fitting of the peaks to functional forms, and therefore it can be easily incorporated as a subroutine in any NMR processing software. Tests on tripeptides have shown that CAKE is a powerful method for volume integration. The substantial independence of CAKE on digital resolution and SNR warrants that it can be safely used for peak integration in three-dimensional spectra. Because of its inherent simplicity the software can be extended to automated integration of three- and possibly higher-dimensionality NMR spectra.

7650-121, Poster Session

Biomedical imaging with THz waves

A. Nguyen, Univ. of California, Irvine (United States)

Radio-frequency (RF) imaging based on the use of radio waves has a long history and several RF-based techniques have been developed and demonstrated. RF imaging is convenient due to the fact that it can be conducted without making a contact to the object, can penetrate deeply into a human body and/or biological tissues and have relatively good imaging contrast between the tissue being imaged and the surrounding. Good imaging contrast is the major advantage of RF imaging as compared to ultrasound imaging.

We present a technique for biomedical imaging using terahertz (THz) waves. THz, the upper end of the electromagnetic spectrum between 300 GHz and 3 THz, is a relatively untapped resource for biomedical applications. As compared to other radio waves at lower frequencies, THz waves have several unique advantages, including extremely small medical devices, extraordinarily fine spatial resolution, and radiation in very small beams much like lasers. The extremely narrow radiation beam allows energy to be focused on tiny spots to examine small areas or tiny objects such as “microscopic tumors.” Just like other radio waves, THz waves do not have ionizing radiation, which imposes hazards such as cancer production, chromosome breakage, and tissue damage. THz waves in the low-attenuation electromagnetic-spectrum windows such as 370-400 GHz may penetrate tissues sufficiently for imaging purposes, especially for those with low-water content (e.g. fatty tissues) or near the surface. Biomedical imaging using THz promises several benefits and is thus valuable for medical applications.

7650-122, Poster Session

Investigation of THz for possible use in medical ultrasound technique

A. Nguyen, Univ. of California, Irvine (United States)

Terahertz (THz), the upper end of the electromagnetic spectrum between 300 GHz and 3 THz, is a relatively untapped resource for biomedical applications. As compared to other radio waves at lower frequencies, THz waves have several unique advantages, including extremely small medical devices, extraordinarily fine spatial resolution, and radiation in very small beams. The extremely narrow radiation beam allows energy to be focused on tiny spots and minimizes the spreading of unwanted radiation into nearby tissues. Just like other radio waves, THz radiation is non-ionizing, avoiding hazards such as cancer production, chromosome breakage, and tissue damage. Ultrasound technique has been used for various medical imaging applications for at least 50 years and is considered as one of the most widely used diagnostic techniques in modern medicine. It was found that acoustic wave, which is the basic wave used in constructing images in ultrasound technique, can be generated from an illuminating radio wave. Radio wave-induced ultrasound technique possesses unique features of non-contact, deep penetration, fine imaging contrast, good spatial resolution, and fast.

We investigate possible use of THz for ultrasound technique to produce enhanced imaging contrast and resolution for achieving high quality and accuracy of biological tissues and human organs imaging for medical applications. The use of THz is particularly suited for this application since THz waves radiate in tiny beams that can focus high energy into micro tissues to produce large thermal-induced acoustic waves needed for enhanced ultrasound imaging. The ability of confining radiation into tiny spots also makes THz well suited for certain technologies such as endoscopic ultrasound to improve minimally invasive diagnostic medical procedures.

7650-123, Poster Session

Monitoring system of arch bridge for safety network management

B. Joo, Y. J. Yoo, C. H. Lee, K. T. Park, Y. K. Hwang, Korea Institute of Construction Technology (Korea, Republic of)

Korea has constructed the safety management network monitoring test systems for the civil infrastructure since 2006 which includes airport structure, irrigation structure, railroad structure, road structure, and underground structure. Bridges among the road structure include the various superstructure types which are Steel box girder bridge, suspension bridge, PSC box girder bridge, and arch bridge. This paper shows the process of constructing the real-time monitoring system for the arch bridge and the measured result by the system. The arch type among various superstructure types has not only the structural efficiency but the visual beauty, because the arch type superstructure makes full use of the feature of curve. The main measuring points of arch bridges composited by curved members make a difference to compare with the system of girder bridges composited by straight members. This paper also shows the method to construct the monitoring system that considers the characteristic of the arch bridge. The system includes various sensor types such as displacements, strain gauges, accelerometers, thermometers, CCTV and so on. For the long term and accuracy monitoring, the latest optical sensors and equipments are applied to the system.

7650-125, Poster Session

Wireless structural health monitoring system of city bridges

S. Cai, J. Su, Research Institute of Highway (China)

Structural health monitoring (SHM) is an active area of research devoted to systems that can autonomously and proactively assess the structural integrity of civil buildings. Structural monitoring

systems using wireless sensors have the potential to serve as low-cost alternatives to commercially available cable-based monitoring systems. However, the current bridge health monitoring systems almost give attention to the large-span cable supporting bridges; these systems are complicated and expensive, for the majority of the other bridges are ignored instead. To better evaluated bridge health status, the key issue is to avoid overruns due to overloading vehicles. Traditionally, the health status monitoring of the general bridges usually was implemented by the methods of human; it is a relatively passive monitoring mode. Moreover, it is difficult to track developments and forecast state of bridge structure. In this paper, wireless vibration sensors are adopted to rough identify the moving force and exact modal analysis to assess the structural condition of bridges. With this methods, it jump out the relatively static regulatory approach in the past, the heavy traffic of middle bridge on our dynamic real-time track areas of whole Hangzhou area, it greatly enhance work efficiency and regulatory standards.

7650-127, Poster Session

Structural damage detection based on non-negative matrix factorization and relevance vector machine

Y. Bao, H. Li, Y. Huang, Harbin Institute of Technology (China); J. Ou, Harbin Institute of Technology (China) and Dalian Univ. of Technology (China)

This paper presents a novel approach to detect structural damage based on combining non-negative matrix factorization (NMF) and relevance vector machine (RVM). Firstly, the time history measurements are decomposed using the wavelet packet transform for extracting the wavelet packet node energy as the damage feature, and construct a non-negative matrix using the wavelet packet node energy index of all time history data measured by multiple accelerometers installed on the different locations of structure. Secondly, for decreasing the effect of measurements noise, reducing dimension of the matrix and extracting the local essential damage features, NMF technique is used to decompose the matrix and get the new representation of damage feature matrix. Lastly, RVM, which is a powerful tool for classification and regression problems, is used to detect the location of potential damage from the reduced damage feature matrix. Numerical study on the Tianjin Yonghe Bridge is carried out to illustrate the damage detection ability of the proposed method and the results show the successful detection of the undamaged and damaged states of the bridge.

7650-128, Poster Session

Fractal theory and wavelet packet transform based damage detection method for beam structures

Y. Huang, Y. Yang, H. Li, Harbin Institute of Technology (China)

In practical application, the presence of noise affects the effectiveness and robustness of structural damage detection methods greatly. And damage is typically a local phenomenon, which may not be captured sensitively by structural dynamic properties. In this study, a new structural damage detection method based on fractal theory and wavelet packet transform for beam structures is proposed, utilizing time, frequency and space domain information effectively. By analyzing the displacement data of every sampling point along the structure subjected to random excitation using Natural Excitation Technique(NExT), the free vibration signals of both structure before and after damage are acquired. Then the undamaged and damaged signals are decomposed into the low frequency region and high frequency region respectively by wavelet packet transform(WPT). The Higuchi's fractal dimension(HFD) is applied to measure the complexity of the measured time series. The structural damage then can be located by the peak value of Kart's Fractal Dimension(KFD) analyzing the spatial information of the calculated HFD values along the structure. To validate the proposed method, a numerical model of a simple supported beam is analyzed. The results demonstrate that the method is capable of detecting damage of beam structures. The successful detection of damage in beams under heavy noise reveals the superior robustness of the method.

7650-129, Poster Session

Wave field characterization for non-destructive assessment of elastic properties using laser-acoustic sources in fluids and eye related tissues

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The age-related changes in the visco-elastic properties of the human lens are discussed with respect to presbyopia for a long time. All known measurement techniques are based on extracted lenses or are damaging the tissue. Hence, in vivo studies of lens hardness are not possible at the moment. To close this gap in lens diagnostics this project deals with an approach for a laser-acoustic characterisation technique.

Laser-generated wave fronts are reflected by the tissue interfaces and are also affected by the visco-elastic properties of the lens tissue. After propagating through the eye, these waves are recorded as corneal vibrations by laser vibrometry. A systematic analysis of amplitude and phase of these signals and the wave generation process shall give information about the interface locations and the tissues visco-elastic properties.

Our recent studies on extracted porcine eyes proved that laser-acoustic sources can be systematically used for non-contacting generation and recording of ultrasound inside the eye. Furthermore, a specific numerical model provides important contributions to the understanding of the complex wave propagation inside the eye. Measurements of the acoustic sources support this approach.

Future investigations are scheduled to answer the question, whether this novel technique can be directly used during a laser surgery for monitoring purposes and if a purely diagnostic approach, e.g. by excitation in the aqueous humour, is also possible. In both cases, this technique offers a promising approach for non-contacting ultrasound eye diagnostics.

7650-71, Session 8a

Stress dependence of guided waves in rails

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A major problem in most modern railways, that use Continuous Welded Rails (CWR), is the almost total absence of expansion joints that can create severe issues such as buckling in hot weather and breakage or pull apart in cold weather. A critical parameter known in the rail industry is the rail Neutral Temperature (NT) that is defined as the temperature at which the net longitudinal force in the rail is zero. When the ambient temperature equals the NT, the rail is stress free, hence an extracted section will not show any appreciable deformation. When the ambient temperature is higher or lower than the NT, the rail is under compression or tension, respectively. Knowledge of the NT provides a method for the indirect measurement of stress/load in the rail. Unfortunately, the measurement of in-situ stress (or NT) is a long-standing challenge for railway owners and operators.

This paper presents recent numerical and experimental studies on the dynamic behavior of Continuous Welded Rails subjected to a static axial stress. The numerical results show how ultrasonic guided waves are sensitive to variation of stress and could be potentially used to estimate the stress level or the neutral temperature in rails.

Experimental results regarding a 5 foot long steel beam subjected to axial load are also shown. The axial load is changed to simulate

the stress in CWR induced by increasing temperatures. At each load considered, stress waves are generated and detected using broadband and narrowband sources. Linear and nonlinear features sensitive to the longitudinal static stress are extracted from the signals recorded.

The present work represents the initial concept phase of a research and development study funded by the Federal Railroad Administration. The ultimate objective of this study is to develop and test a prototype system that uses non-contact dynamic sensing to measure in-situ rail stress in motion, to determine Rail Neutral Temperatures and the related Incipient Buckling Risks in CWR.

7650-72, Session 8a

Monitoring stress in materials using diffuse ultrasonic backscatter

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Monitoring stress in structures is very important for various safety reasons. One of the challenging problems is to estimate stress nondestructively in various structural components due to changes in loading conditions so that accurate maintenance can be taken before failure. In this presentation, diffuse ultrasonic backscatter is discussed with regard to its potential for measuring and monitoring uniaxial stress in metals with a focus on the experimental implementation. Ultrasonic backscatter occurs when incident ultrasonic energy is scattered from heterogeneities (in this case grain boundaries) in the material. When an applied load is introduced, third-order elastic behavior of the grains results in changes to the received backscattered energy. Uniaxial loading experiments on samples of steel, aluminum, and a magnesium alloy highlight the utility of this approach for monitoring structural components under stress. Different scattering modes are shown to have different sensitivity to the applied load. Specific application of this technology for quantification of rail stress is also discussed. These results are anticipated to impact ultrasonic nondestructive evaluation of heterogeneous media under stress. [Work supported by US FRA]

7650-73, Session 8a

Guided wave propagation as a measure of axial loads in rails

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Measurement of the temperature induced axial load in rails is of interest to railway operators as a too large tensile load will reduce the fatigue life of the rail while a compressive load may cause of buckling of the rail and train derailments. Guided wave propagation has been proposed as a means to measure and monitor the axial loads in continuously welded railway rails although no practical system has been developed. This paper will investigate some of the issues that have to be addressed before such a measurement system can be realised.

The paper will quantify the influence of axial load on the guided wave propagation characteristics. This analysis will be performed by the semi-analytical finite element method, extended to include axial loads. This approach makes it possible to automate the computation of the phase and group velocities of 20 or 30 modes of propagation over a large frequency range for different axial loads.

The suitability of different modes and frequency ranges will be investigated based on the sensitivity of the wave propagation characteristics to axial loads. Methods for measuring the wave propagation characteristics in practice will be proposed and evaluated. The sensitivity of these measurement methods to other changes in the rail will be investigated to determine whether the influence of axial load can be separated from other changes that occur in a practical railway system.

7650-74, Session 8b

Ultrasonic acoustic health monitoring with neural network pattern classification of power spectral density

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This paper presents a generic passive non-contact based acoustic health monitoring approach using ultrasonic acoustic emissions (UAE) to facilitate classification of bearing health via neural networks. This generic approach is applied to classifying the operating condition of conventional ball bearings. The acoustic emission signals used in this study are in the ultrasonic range (20-120 kHz), which is significantly higher than the majority of the research in this area thus far. A direct benefit of working in this frequency range is the inherent directionality of the microphones capable of measurements in this range, which becomes particularly useful when operating in environments with low signal to noise ratios. Using the UAE power spectrum signature, it is possible to pose the health monitoring problem as a multi-class classification problem and make use of a single neural network to classify the UAE signatures. Artificial training data, based on statistical

properties of a significantly smaller experimental data set is created using the combination of a normal distribution and a 2-dimensional coordinate transformation. The combination of the artificial training methods and ultrasonic frequency range being used results in an approach generic enough to suggest that this

particular method is applicable to a variety of systems and components where periodic acoustic emissions exist.

7650-75, Session 8b

Damage location in composite components using ultrasonic sensors and artificial neural networks

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Modern aircraft, wind turbines, and space stations, along with other aerospace structures are expected to be in operation well beyond their design life. Therefore, maintenance is a major concern for these new aerospace systems and a structural health monitoring system (SHMS) is an essential tool to provide for safe operation. The SHMS selected for this study consisted of piezoelectric actuator and sensors combined to form an ultrasonic system. A series of experiments was conducted, using a composite test specimen of eight plies and various fiber directions to evaluate the analysis capabilities of artificial neural networks in this application. Three piezoelectric sensors and one actuator were attached to the test article. Through multiple scans of the ultrasonic system damage at various locations were simulated in the test article. An artificial neural network was created and trained on these sets of simulated damage, followed by a testing of the system with physical, permanent damage to the test piece. The artificial neural network, once trained, was found to be able to locate the damaged areas, using small number of piezoelectric sensors. The research demonstrated that artificial neural networks can be used with measured signals from an ultrasonic system to locate damage in a composite structure. The artificial neural network was developed in such a way to allow for the adaptability onto a multitude of various composite and structural configurations, once trained by a simulated damage routine. The abilities of artificial neural networks to provide fast, accurate analysis for ultrasonic testing data has given promise to a possible SHMS in the near future.

7650-76, Session 8b

Arch bridge suspender tension identification by using neural network

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The measurement of arch bridge suspender tension using vibration

method is mostly considered that the suspender is idealized as taut strings. This idealization simplifies the analysis but may introduce unacceptable errors in many applications by ignoring the boundary condition and bending stiffness effects. The neural network intelligent methodology is proposed to compute suspenders tension, and design steps and optimization methods of neural network are given. In order to get correct neural network predictive model, 200 data of 20 bridges is used to train the neural network. The applicability of the proposed intelligent methodology is verified by comparison with the others method through a case. The result shows that the error isn't beyond percent of 6.

7650-77, Session 9a

Electro-mechanical impedance investigations on a complex satellite structure

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Authors focus on evaluating the structural integrity of a satellite in regards to bolted fasteners. Current dynamic testing procedures are extensive and provide a global evaluation with limited capability of identifying potential problems that could be quickly fixed. Structural health monitoring is being considered as a solution to truncating testing time. This work explores the electro-mechanical impedance method utilizing piezoelectric wafer active sensors. Authors work toward developing an understanding of the physical phenomena associated with structural changes in the form of local stiffness alterations and correlating that structural change with changes in impedance measurements. Damage is represented by inadequately preloaded bolts at incremental torque loads. Studies also focus on possible assembly error scenarios including: loose bolts, improper component location/orientation, and loose component wires. A broad frequency spectrum is explored to find the optimal window, and this window is observed for consistency and dependence on factors indirectly related to the structure. Peaks present in measurements are tracked for changes in amplitude, frequency, and shape. Initial results demonstrate that various scenarios can be traced in impedance measurements and are repeatable.

7650-78, Session 9a

Determination of the speed of ultrasound in thin materials by observation in reflection or transmission

U. Amjad, A. M. Esam, W. Grill, Univ. Leipzig (Germany)

With the aid of phase contrast acoustic microscopy, the material properties related to mechanics including the speed of ultrasonic waves can be determined. For this purpose the observed variation of the magnitude and phase with the variations in the thickness of the sample are compared to modeling. The method relates to the observation of the so called Newton's rings in optics, but with time resolved generation and detection which is used in the acoustical analogue to suppress interferences for sufficiently extended objects. Both methods are presented, including experimental data, and discussed. Applications involve also observations on microscopic scales with a lateral resolution of 1 µm. Some of the principles involved for modeling at the resolution limits are exemplified here also on larger scales to demonstrate the reliability of the developed schemes.

7650-79, Session 9a

Experiments on focusing and use of acoustic energy to enhance the rate of polymer healing

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Minor structural damage to orbiting light weight space structures can significantly affect the functionality of such structures. Often the damage may be caused by collisions with space debris and micrometeorites, and is difficult and/or economically challenging to repair during service. It is therefore worthwhile to consider self healing materials and structures for missions where manual recovery and repair are ruled out as options. A number of innovative approaches to self healing are currently being developed around the world. Many of these developments are at the materials level, however. Our study considers the problem from a structural point of view, while recognizing that healing occurs at the molecular/materials-level. In particular, the current emphasis is on investigating whether crack healing to the point of full mechanical recovery can be accelerated using focused acoustic energy.

We present here recent results on an acoustic focusing method based on time reversal mirrors. Experimental results demonstrating time reversed focusing at the site of a 'defect' are presented. Current experiments use time reversed focusing of a pulse in a metal rod, with piezoceramic transducers providing the acoustic energy. LabView software with FPGA (field effect programmable gate array) hardware is used in this implementation. Concurrent with this effort, we are also investigating the effect of acoustic radiation on polymer healing. For this purpose, we consider polymer curing as an analogue to crack healing, and study the effect of acoustic energy on the curing of a 2-part epoxy in a tube as monitored using impulse response measurements and direct spectroscopic observations. While the impulse response measurements provide a global structural measure of the extent of curing, the spectroscopic measurements enable materials-level observations of the evolving chemical structure. Experimental results on this component are also discussed, with a particular emphasis on spectroscopic measurements tracking the curing process with and without acoustic radiation in a low-temperature environment.

7650-80, Session 9a

Micro-elastic property characterization of chitosan films by phase-sensitive acoustic microscopy

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The biomaterial chitosan is used in the paper manufacturing industry, as a wound healing agent and in filtration amongst others. In this paper, the micro-elastic properties of films of chitosan of varying thickness are investigated with the phase-sensitive acoustic microscope (PSAM). The models for the evaluation of material properties for the films are thickness dependent and enable the determination of the Young's moduli for films ranging from 200 nanometers to over 40 micrometers. The PSAM presents a non-invasive method for the effective characterization of soft films.

7650-81, Session 9b

Damage detection in a sandwich honeycomb panel via analysis of vibration signatures

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There is a pressing need to develop effective techniques for structural health monitoring (SHM), so that the safety and integrity of the structures can be improved. Honeycomb sandwich panels are used for structures because of their high stiffness, good fatigue resistance and low weight. These panels are used in a variety of applications, but particularly in the aerospace industry. In real-life situations these panels can be affected by defects and impacts, and it is important to know the effects of these defects and the behavior of the damaged panel;

it also important to determine the location of the defect. The main objective of this study is to evaluate damage detection techniques for a sandwich honeycomb plate using vibration signatures obtained from different tests. The numerical finite element (FE) analysis is also performed to complement the damage detection. The study comprises of testing two aluminum-Nomex sandwich honeycomb plates - one with no faults, and the second with a delamination contained within the plate at a known location. The delamination is introduced between the plate and the honeycomb structure covering a known area. Vibration response data is collected and characteristics of the sandwich plate are extracted, from which the location and magnitude of the damage are evaluated. Signal processing algorithms are employed to improve the damage detection and location capability. The signal processing algorithms used include wavelet transform and spectral cross correlation. These are built into a LabVIEW interface that integrates and automates the hardware and software operations and displays the results for the tests. The effectiveness of each for SHM in sandwich honeycomb aluminum panels under the given conditions is then investigated.

7650-82, Session 9b

Bicoherence-based structural health monitoring of fixed offshore structures

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Structural integrity management is key to the safe and economic operation of offshore structures (for example those used to support oil and gas platforms and wind turbines). Presently, regular manual inspections are conducted, which are expensive, time consuming, often dangerous, and prone to human error. This paper investigates the possibility of using the bicoherence function of the measured structural acceleration, which naturally arises from environmental loading, to provide automatic early detection of damage in an offshore structure.

The bicoherence function estimates the non-linear content in the measured structural response, which arises from bi-linear stiffness effects in fatigue cracked structural members. This estimate can be used as a damage indicator. Other types of non-linearity, such as that resulting from the non-linear drag force associated with ocean wave loading, are not detected, making this a highly targeted method for detecting fatigue cracking.

A detailed simulation study is conducted, using a realistic oil drilling platform model and realistic stochastic wave loading. Progressive damage representative of fatigue cracking is introduced to individual highly utilised structural members, and the resulting structural acceleration signals are used for damage identification. It is demonstrated that very small changes in stiffness (less than 10%) of individual structural members are detectable from measurements of global structural motion. Additionally, the bicoherence is shown to be insensitive to normal operating parameter variations (such as mass and damping changes) and to variations in wave excitation force, making the method extremely attractive for structural health monitoring in offshore structures.

7650-83, Session 9b

Damage detection of structures under unknown input with several measured responses

K. Zhang, Z. Duan, Harbin Institute of Technology (China); S. Law, The Hong Kong Polytechnic Univ. (China)

Early damage detection of structures under operational loads plays a significant role in the fields of aerospace, mechanical and civil engineering. Among the existing damage detection methods, system identification techniques using only measured structural responses to identify modal or structural parameters invoked great interests in the past decades since external excitations such as wind excitation, vehicular excitation, ground motion or ground microtremor etc can not be obtained or accurately measured under actual operating conditions. This is particularly true for large civil engineering structures such as tall buildings, long bridges and offshore platforms etc.

In this study, a new method is proposed to detect local damages of structures from only several measured structural responses by simultaneously identifying structural physical parameters and unknown input. The unknown input force is represented by orthogonal polynomial approximation, and the sensitivities of dynamic response with respect to the structural physical parameters and the orthogonal coefficients of forces are derived analytically. The identification equation is set up and is solved with the damped least-squares method in an iterative procedure. A nine-bay three-dimensional frame structure serves as an example for validating the proposed method. Numerical simulations with measurement noise and initial model errors show that the proposed method can accurately simultaneously detect local damages and identify unknown input time history from only several acceleration responses of the structure. This method provides a new approach for damage detection of structures with unknown input and incomplete measured output information.

7650-84, Session 9b

Machine learning algorithms to damage detection under operational and environmental variability

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Real-world structures are subjected to operational and environmental condition changes that impose difficulties for detecting and identifying structural damage. In fact, the authors believe that separating changes in sensor readings caused by damage from those caused by changing operational and environmental conditions is one of the biggest challenges for transitioning structural health monitoring (SHM) technology from research to practice. As such, the main goal of this paper is to detect damage with the presence of such operational and environmental variations using vibration-based damage identification procedures. Four machine learning algorithms based on auto-associative neural networks, factor analysis, Mahalanobis distance, and singular value decomposition are applied in order to create a damage indicator that is invariant under operational and environmental variations. A base-excited three-story building structure was tested in laboratory environment to obtain time series data from an array of sensors under several structural state conditions. Tests were performed with varying stiffness and mass conditions with the assumption that these sources of variability are representative of changing operational and environmental conditions. Damage is simulated through nonlinear effects introduced by a bumper mechanism that simulates a repetitive impact-type nonlinearity. This mechanism intends to simulate the cracks that open and close under dynamic loads or loose connections that rattle. This study performs a direct comparison of four proposed machine learning algorithms that have been reported as reliable approaches to separate structural conditions with changes resulting from damage from changes caused by operational and environmental variations.

7650-85, Session 10a

Generalized representations and universal aspects of Lamb wave dispersion relations

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Due to the dependence on a limited amount of parameters, the dispersion relations of Lamb waves can be presented in a generalized way. This is exemplified for different established typical representations. Special attention is given to the representation of the momentum on energy, which is well suited to discuss basic features since energy and momentum are the two properties that are strictly conserved in loss free homogeneous materials. Representations involving the

phase and group velocities and the time-of-flight are also discussed. The dispersion relations display features related to level crossing of interacting modes. Furthermore degeneracies caused by symmetry respectively limit value effects are discernible including relations to basic mechanical properties relevant for Lamb waves. A discussion of these effects is included in the presentation.

7650-86, Session 10a

A time domain spectral element model for piezoelectric excitation of Lamb waves in isotropic plates

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By minimizing the discretization errors associated with the spatial discretization in conventional FEM, the spectral element method (SEM) is an efficient method for solving elastodynamic problems, with computational economy attributed to the diagonal mass matrix when SEM is implemented in Legendre setting. In the present work, the SEM in the time domain is presented, starting from a variational statement of the problem, discretizing the domain in a similar way to the conventional FEM. Due to the high order approximation, there is no need for isoparametric mapping of each element into the reference domain. The approximate solution is expanded in terms of high order Lagrange polynomials constructed on a non uniformly spaced nodes corresponding to the zeros of the weighted first derivative of Legendre polynomials. The SEM compares well with the higher order finite difference schemes in terms of minimum number of points per wavelength required to resolve a wave. A 2D model based on Legendre SEM of a PZT patch coupled with an isotropic plate is detailed, based on coupled piezoelectricity and elastodynamic equations, both bounded plate and infinite plate -via perfectly matched layer boundary- is implemented. Both the actuator and sensor behaviors were accounted for, as well as the dynamic behavior of the substructure and electromechanical interaction between the PZT patch and the plate. The simulation results are validated experimentally using a notched aluminium plate with surface bonded PZTs, for both actuation and sensing. Good agreement between simulation and experimental results is demonstrated for the first Lamb modes A0 and S0, for a frequency band up to 1 MHz on a 1 mm thick plate.

7650-87, Session 10a

Simulation and experimental validation of guided-wave excitation and propagation in composite plates

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Composites are one of the most widely employed polymers in the modern industries such as aviation, energy and infrastructure because of their high strength, low density, high stiffness, and long fatigue life. The ability of the composites to customize and give directionality to the physical properties greatly increases the prospects of their usage in the future. Due to their current and increasing demand, development of an appropriate structural health monitoring (SHM) is pivotal. Guided waves (GW) render a good prospect for SHM due to their ability to travel long distances over the surface as well as through the thickness of a structure. Studies have shown GW as an efficient method for damage detection in metallic structures, which motivates similar research in the field of composite materials. Because of the anisotropy present in the composite materials, the development of the SHM methods are significantly more complicated and challenging than in the case of isotropic materials. The present study investigates the propagation of GW in composite plates with the help of theoretical modeling and experimentation.

The proposed paper will start with the theory of GW propagation in composite laminates, followed by a review of GW excitation and sensing by a finite dimensional piezoelectric transducer. The theory is based on 3D elasticity, where admissible wavenumbers associated with the each propagating mode are first determined in a bulk transversely isotropic material. These are then used to express displacement and stress fields for a composite layer. A given composite laminate is then analyzed as a series of laminae, where enforcing displacement and stress continuity conditions at the interface between layers yields a set of equations which are solved by the global matrix approach. Global matrix also yields the wave phase and group velocities associated with the composite laminate. The second part of the theory deals with the response of a piezoelectric sensor to the GW field in composite laminates.

Two different types of experimentation procedures (piezoelectric sensors and laser vibrometry) are used. They are employed to verify the accuracy of the theoretical simulations in the time, frequency and space domains. Piezoelectric transducers generate the required GW for experimentation. For the first method, piezoelectric sensors bonded on the surface of the composite structure measure the different aspects of GW field. The experiment is repeated by changing different parameters such as frequency, azimuthal angle and dominant mode of propagation. The non-intrusive technique of laser vibrometry is used to complement the procedure with piezoelectric sensors, which can acquire data only from the discrete points where they are located. Laser Vibrometer provides information about the spatial variance of the GW field that is used to compare the radial attenuation as predicted by the theory at different azimuthal angle positions. Since the orientation of the laminae present in the composite laminate decide its properties, the whole set of experiments will be carried out for different categories of composite laminates.

7650-88, Session 10a

Modeling coupled piezo-elastodynamic behavior of piezoelectric actuators for guided wave propagation

G. Huang, F. Song, Univ. of Arkansas at Little Rock (United States)

Guided waves generated by a piezoelectric actuator/sensor system have shown great potential for the health monitoring of thin wall structures, which requires more effective models to accurately predict the coupled dynamics behavior. In contrast to most of previous models, the current model is based on three-dimensional linear elasticity and also takes into account the coupled electromechanical behavior of a piezoelectric actuator boned to a plate structure. The proposed model is then used to simulate the guided wave propagation generated by piezoceramic actuators/sensors. The analytical predictions from the current model are finally validated by the comparison with the results from the corresponding finite element simulations. The effects of the material mismatch and loading frequency upon the resulting guided wave propagation are discussed.

7650-89, Session 10a

Modeling of transient Lamb wave propagation in a honeycomb composite sandwich structure

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A semi-analytical model based on the wavenumber integral representation of the elastodynamic field is developed in an effort to understand the characteristics of the guided Lamb wave propagation in a honeycomb composite sandwich plate. The honeycomb composite used in this study has an extremely lightweight and relatively thick regular hexagonal honeycomb core, which is sandwiched between two graphite woven composite skins. The estimated homogenized material properties of the aluminum honeycomb core are found to be quasi-isotropic in nature with an axial symmetry about the thickness direction. In order to take the advantage of the axial symmetry, the displacements are expressed in terms of suitable potential functions. Ultimately, the displacement and stress components in each layer (skin or core) are represented in the fourier domain in terms of six unknown constants, which are solved by applying the interface continuity conditions and the stress conditions on the free surfaces.

The semi-analytical model has been validated with laboratory testing and a 2D finite element model. It has been shown that the model is quite reasonable in capturing the behavior of the waves in relatively low frequency applications of interests, where the wavelength is larger than the honeycomb cell dimensions. Preliminary theoretical modeling indicates that the guided waves have sinusoidal depth dependence in the composite skin but they decay exponentially in the honeycomb core. Thus the guided waves are of the so-called Rayleigh-Lamb (R-L) type. Extension of the model to include disbonds at the core-skin interface and other defects is under way.

7650-90, Session 10b

Vulnerability analysis for design of bridge health monitoring system

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The recent engineering applications on health monitoring of large scale bridges show that although hundreds of sensors were installed on a structure and a great amount of data were collected from the monitoring system, it is still of great difficulties to precisely assess its physical condition as well as to give an accurate alarm on structural damage. Thus, the allocation of sensors and the design of early warning system become two of the most important tasks performed during structural health monitoring system design. Vulnerability, in its original meaning, is the system susceptibility to local damage. For a structural system, the vulnerability can thus be regarded as structural performance susceptibility to local damage. The purpose of this work was to develop and investigate structural vulnerability analysis to obtain monitoring components which are more vulnerable than others and the corresponding warning threshold once damaged. The structural vulnerability performance to different damage scenarios depends upon structural geometrical topology, loading pattern on the structure and the degradation of component performance. A two parameters structural vulnerability evaluation method is proposed in this paper, which are the damage consequence and the relative magnitude of the damage scenarios to the structural system. Structural vulnerability to different damage scenarios can be regarded as the tradeoff between the two parameters. Based on the results of structural vulnerability analysis, the limited structural health monitoring resources can be placed optimitically. The quantitative approach is illustrated on the design of bridge health monitoring system for a cable-stayed bridge.

7650-91, Session 10b

Temperature effects on modal parameters and its experimental validation

Z. Min, L. Sun, Tongji Univ. (China)

Abstract: Based on one year monitoring data of a cable-stayed bridge, it was found that the environmental temperature was one of principal environmental factors effecting structural modal parameters in long-term. The possible mechanism is that the environmental temperature influences material properties, such as modulus of elasticity, and structural geometry properties, such as boundary conditions. In this paper, the distribution of environmental temperature were analyzed based on the long-term monitoring data of a cable-stayed bridge firstly. It was found that the distribution of structural temperature was consistent in longitudinal direction of bridge and the structural temperature gradients in RC box girder section were non-Gaussian distribution. And then the effects of temperature on modal parameters was analyzed by ARX (Auto-Regressive model with eXogenous inputs) model based on the monitoring data. It was found that there was obvious time-delay when the environmental temperature effecting the modal parameters and this delay time was about 7-8h. The effects of temperature on modal parameters was also simulated by a FEM model which was updated according to the monitoring data and some significant conclusions were found. Finally, the effects of environmental temperature on modal parameters was validated by a model experiment, and the results were consistent well with the theoritical analysis.

7650-92, Session 10b

Effect analysis of environmental factors on structural modal parameters of cable-stayed bridge

Z. Min, L. Sun, Tongji Univ. (China)

Influenced by some environmental factors (such as temperature, traffic loads, wind and rainfall etc.), dynamic properties of bridge system would change. In this paper, one year monitoring data of the main navigation channel bridge of Donghai Bridge were analyzed and some statistical results were presented. Based on coherence analysis and correlation analysis, the main environmental factors affecting structural modal parameters, were confirmed. It was showed that the temperature and structure vibration magnitude were two main influencing factors on the variation of bridge modal frequency. The structural modal parameters were significantly affected by wind only when the wind speed was high enough. Moreover, the analysis results showed that these three factors affect structural dynamic properties in different time scale: the temperature change was accountable for yearly variation of bridge modal parameters, the acceleration RMS (root mean square), which indicated the structural vibration magnitudes, was accountable for their weekly variations and the wind affects structural modal parameters in transient strong wind term. Finally, the mechanism of environmental effects on frequency variation was discussed based on above analyzing result.

7650-93, Session 10b

Time-series models for identifying damage location in structural members subjected to ambient vibrations

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One of the main challenges of vibration-based health monitoring of bridges and other civil infrastructures is the source of excitation. Using ambient vibrations as an excitation source is one of the few choices that allow continuous health monitoring without in-service interruption. This paper presents a vibration-based health monitoring approach used to identify damage location in structural members. The concept is demonstrated using a simply supported two span steel beam, instrumented with 15 accelerometers and subjected to simulated ambient loadings. The ambient loadings were simulated by applying random loads at a location along the length of the beam using an electro-hydraulic actuator.

The vibration time histories were collected at different conditions of the beam including undamaged and induced damaged conditions. Damages were introduced to the beam by cutting notches of different sizes at different locations. The recorded time history of the undamaged condition of the beam was taken as the reference data set and indirect comparisons were made between the reference data set and damaged data sets in order to predict damage locations along the beam. The collected data sets were divided into smaller data samples and damage features were extracted by fitting AR and ARX time series models to different data samples. Statistical distributions for damage features were investigated and used to determine the probability of damage occurring at different sensor locations. The research findings demonstrate success of the approach by showing higher probability values at the sensor locations which were located close to the physical damage locations.

7650-94, Session 10b

A novel non-parametric sequential probability ratio test method for structural condition assessment

Z. Min, L. Sun, Tongji Univ. (China)

In this paper, a novel non-parametric sequential probability ratio test

method was proposed based on Mann-Whitney rank-sum test for structural condition assessment by ultilizing long-term structural health monitoring data. Compared with a fixed sample size test method, the method of sequential probability ratio test had many advantages and was widely used in hypothesis testing. When one use these methods in the process of hypothesis testing, a probability distribution function of the samples was need to be assumed, for examples, Gaussian or Exponential distribution function. However, sometimes the actual probability distribution function of the samples was unknown or could not be expressed as a simple distribution function. Under the assumption that the samples of the bench condition was known, the log-likelihood ratio of Mann-Whitney rank-sum of the samples of unknown condition was calculated accurately and the decision was made by comparing with the threshold. This method did not require to konw the probability distribution function of the samples, so it could be applied to the conditions with different probability distribution functions. Finally, the method was validated by numerical examples. The results showed that this proposed method was effective to distinguish different conditions and was better than other non-parametric sequential probability ratio test method.

7650-95, Session 11a

The influence of disbond defects on Lamb wave testing in GLARE composites

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GLAss-REinforced (GLARE) laminate is a new class of fiber metal laminates (FML), which are hybrid composites consisting of thin alternating bonded layers of metal sheets and fiber-reinforced epoxy prepreg. GLARE composites provide better properties such as advanced mechanical properties, outstanding fatigue resistance, excellent impact resistance, and fire resistance. GLARE composites have been used in a substantial part of the fuselage of the aircrafts, such as Airbus 380, due to the superior properties. In this paper, the influence of disbonds on Lamb wave testing in GLARE composites will be described. Guided Lamb waves were launched and detected with Polyvinylidene Fluoride (PVDF) comb transducers. Disbond defects were introduced to study their influence on the Lamb wave signals. Both the amplitude and the travel time of the Lamb waves show distinct differences with and without disbonds, which can be used to monitor the disbond growth. Changes in the amplitude of the Ao mode Lamb wave as well as the time of travel are correlated to disbond size. In addition, thermal imaging and acoustic full-field imaging were applied to inspect the disbond region to cross-correlate the disbond size with its influence on the Lamb wave signals measured by the PVDF sensors.

7650-97, Session 11a

Damage detection in adhesively bonded lap joint under impact load: finite element modeling and simulation

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Adhesively bonded joints have been extensively used in aerospace, automobile, construction and naval architecture industries. Those joints have advantages over conventional joints such mechanical connecting and welding since the adhesive joints have less sources of stress concentrations, more uniform distribution of load, and better fatigue properties. To compete with the conventional joints, there have been research topics to be extensively investigated. The first one is the development of mathematical models to analyze the behavior of those joints. Both analytical and numerical models have been developed. Among the numerical models, the finite element method has been extensively used. The single-lap joint has been used in most of the studies due to its simplicity and practical application. The second one is the development of nondestructive testing tools to prevent severe accidents owing to mechanical damages in adhesive layers. For the second development, investigators have used ultrasonic waves and relatively low frequency waves for capturing thickness reduction of adhesive zones, deterioration of adhesive materials, voids in adhesive layers, etc. To detect a certain damage or defect, it has been shown that transmitter and receiver arrangement is important. This study presents how we can detect those damages using elastic waves by constructing finite element simulation. For the study, we assume that loading condition is an impact, which possibly damage the adhesively bonded lap joint. Various shapes of rigid bodies are considered for the impacting loads. For finite element simulation, ANSYS is used for three-dimensional modeling and impact analysis.

7650-98, Session 11a

Understanding a reference-free impedance method using collocated PZT transducers

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Conventional EM impedance based damage diagnosis identify damage by comparing “current” impedance signals with “baseline” ones obtained from the pristine condition of a structure. However, in reality, structures are subject to changing environmental and operational conditions that significantly affect measured impedance signals and these ambient variations can often cause frequent false-alarms.

In this paper, a new concept of a reference-free impedance method, which dose not require direct comparison with a baseline impedance signal, is proposed for damage detection in a plate-like structure. A single pair of piezoelectric transducers (PZTs) collocated on both surfaces of a plate are utilized for extracting electro-mechanical (EM) impedance signatures associated with mode conversion due to damage. A finite element (FE) and a spectral element (SE) analysis are conducted to investigate the EM characteristics of collocated piezoelectric transducers (PZTs) in the frequency domain at the presence of damage such as crack and delamination in a structure. Then, the EM signals induced by damage are extracted using the signal decomposition technique based on the polarization of the collocated PZTs. The effects of the size and the location of damage on the decomposed EM signals are investigated as well. Finally, the applicability of the decomposed EM signals to the reference-free damage diagnosis is discussed.

7650-99, Session 11a

Sensor optimization for progressive damage diagnosis in complex structures

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Online diagnosis of progressive damage is a significant step towards real-time implementation of structural health management (SHM) systems. Recently, a sequential Monte Carlo (SMC) method was developed to diagnose progressive damage. This relies on a hybrid approach that combines physics-based damage evolution with hidden Markov model-based models on how measurements relate to damage. These measurements are assumed to have been collected from a known fixed multi-sensor configuration. However, it is important to consider optimizing the sensor configuration to improve estimation performance while reducing sensor cost and processing time. For example, the sensor configuration could be optimized to: (a) reduce the estimation mean-squared error (MSE); or (b) find and use only those sensors that will increase some damage information measure; or (c) infer damage location in the minimum number of time steps.

In this paper, we propose an SMC-based progressive damage diagnosis framework using the aforementioned hybrid approach while optimizing the sensor configuration. The proposed approach adaptively configures the sensors based on minimizing the predicted MSE. We will consider two different methods for the optimization. We will first perform a global optimization over the entire search space of all available sensors. In the second method, we will perform a hierarchical or multi-level optimization, where an iterative strategy will

configure only a subset of available sensors in a tree-like fashion. As we will demonstrate, the second method is more efficient for real-world damage identification scenarios. We will demonstrate the effectiveness of our approach by diagnosing damage in a complex structure.

7650-100, Session 11b

Micro patterning processes for thin film nitinol endografts and evaluation of endothelialization in swine model

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Micro features were created in thin film nitinol using a novel lift-off process for endovascular biomedical devices. This manuscript describes problematic fabrication process of wet etching and first introduces an effective way, named “Lift-off” process to solve undercut and non-uniform pattern issues.

Two lift-off processes (i.e., lift-off I and II) were discussed. Lift-off I process is making posts by dry etching technique and obtaining the deposited thin film nitinol at the bottom of the etched Si substrate surface. Lift-off I process had fracture issues while the film is peeling off from the substrate due to high aspect ratio post structures, therefore, lift-off II process was proposed. Lift-off II process is the method creating trenches instead of posts on the Si substrate using dry etching technique, then thin film nitinol is depositing on the patterned Si substrate. Fabricated micro patterns includes various shapes (i.e., ellipse, diamond, circle, square, etc.) and different physical dimensions in the range of 5~60μm. SEM images evaluate issues of the lift-off I process and verify the smoothness of the patterned thin films produced by lift-off II process.

In-vivo tests in swine were performed to evaluate the endothelialization through the fabricated micro patterns. Angiography two weeks after delivery confirmed patency of the arteries. SEM images showed uniformly promoted endothelial layer covering without thromobosis. Pathological studies were also performed to assess the endothelialization and the neointimal hyperplasia through the 30x60μm diamond shaped patterns on thin film nitinol.

7650-101, Session 11b

Study of thickly sectioned breast cancer tissue with scanning acoustic microscopy

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The present study is to investigate the feasibility of in-vivo acoustic microscopy applied to a breast cancer tissue analysis. The study was implemented with mechanical scanning reflection acoustic microscope (hereinafter simply called “SAM”) by the following procedures. First, we ultrasonically visualized thickly sectioned normal and abnormal tissues to determine the lowest transducer frequency required for cellular imaging, wherein the abnormal tissue includes a cancer tumor having gropes of cancer cells. The thick tissues were thinly sectioned for optical and high-frequency-ultrasonic imaging for pathological understanding. Second, we ultrasonically visualized subsurface cellular details of thick tissue specimens with different modes (i.e., pulse and ton-burst wave modes) to obtain the highest quality of the ultrasonic images for future design of the in-vivo SAM with a single element transducer and/or a phased array transducer. Third, we developed a mathematical modeling (angular spectrum approach) and computer simulation software to analyze the transducer output to characterize a breast cancer tissue. The numerical results were compared to experimental.

7650-102, Session 11b

Synchronous monitoring of muscle dynamics and muscle force for maximum isometric tetanus

M. Zakir Hossain, W. Grill, Univ. Leipzig (Germany)

Skeletal muscle is a classic example of a biological structure-function relationship. At both macro and microscopic levels, skeletal muscle is exquisitely oriented for force generation and movement. In addition to the dynamics of contracting and relaxing muscle which can be monitored with ultrasound, variations in the muscle force are also expected to be monitored. To observe such changes synchronously for the gastrocnemius muscle a novel detection scheme has been developed. As already introduced for the detection of sideways expansion of the muscle, ultrasonic transducers are mounted sideways on opposing positions of the skin. To detect variations of the muscle force, angle of pull of the muscle has been restricted by the mechanical pull of the sonic force sensor. Under this condition, any variation in the time-of-flight (TOF) of ultrasonic signals can be introduced by a variation of the TOF along the path of the ultrasound transit signal. The observed variations of the TOF are compared to the signals obtained by ultrasound monitoring for the extension and dilatations observed for free sideways motion. The general behavior of the muscle dynamics and force shows almost an identical concept. Since muscle force also relates the psychological boosting-up effects the influence of boosting-up on muscle force and muscle dynamics can also be quantified form this study. Length-tension or force-length and force-velocity relationship can also be derived quantitatively with this monitoring.

7650-103, Session 11b

Warped frequency transform analysis of ultrasonic guided waves in long bones

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Long bones can be seen as irregular hollow tubes, in which, for a given excitation frequency, many ultrasonic Guided Waves (GWs) can propagate. The analysis of GWs is potential to reflect more information on both geometry and material properties of the bone than other methods such as dual-energy X-ray absorptiometry, or quantitative computed tomography, and can be used in the assessment of osteoporosis and in the evaluation of fracture healing.

In this study, time frequency representations (TFRs) were used to gain insights into the expected behavior of GWs in fractured long bones. To this aim, we implemented a dedicated Warped Frequency Transform (WFT) which decomposes the spectro-temporal components of the different propagating modes by selecting an appropriate warping map to reshape the frequency axis. Time-transient events obtained both numerically, from dedicated FEM simulations, and experimentally, via a piezoelectric ultrasonic set-up applied to fractured bovine tibiae, are analyzed. In FEM simulations, the bone is considered as a hollow cylinder with inner and outer diameter of 18.8 and 24.7 mm, respectively, and linear dry poroelastic material properties in agreement with the low level of stresses induced by the waves. The results show that WFT limits interference patterns which appear with others TFRs (such as scalograms or warpograms) and produces a sparse representation suitable for characterization purposes. The transformation is used to extract GWs dispersive velocity and frequency-dependent attenuation. In particular, the mode-frequency combinations propagating with minimal losses are identified, as they are suitable for the evaluation of fracture healing.

7650-104, Session 11b

Correlation between acoustic emission activity and failure patterns of the anterior cruciate ligament under uniaxial tension

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The failure of the anterior cruciate ligament (ACL) represents a sequence of interrelated procedures that are related to the biomechanical properties of the distinct fiber bundles, mainly the anteromendial (AM) and the posterolateral (PL). In a previous study on the biomechanical response of the ACL, three different patterns were recognized, where a complete or partial tear of the fiber bundles were preceding while the remaining intact fiber bundles have a potential load resistance. The key objective of the current study is to correlate macroscopical response and acoustic emission (AE) activity. Furthermore we aim to use AE as a tool for the confirmation of the distinct role of the AM and PL bundles during rupture of the ACL. For this purpose, AE transducers were placed on both the tibia and the femur, and stress wave signals during tension were monitored. A correlation between AE activity and failure pattern was attempted via the employment of appropriate descriptors.

7650-105, Session 11b

Smart mobility solution for patient home monitoring

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Home monitoring solutions are becoming increasing popular in patient healthcare. In addition to providing therapy, the medical devices also monitor vital patient health parameters like pressure and electrical activity of the heart. This includes looking out for arrhythmias and recording any significant events that may take place. This recorded data is of interest to the physician and it helps to decide further actions on the basis of this data collected.

In case a device is implanted for health monitoring, the patient need to visit the physician for follow-up visits. These visits are more frequent to begin with and may happen on an ongoing basis every 2 to 3 months. If such follow up is done in a clinic, then in between visits, the physician has no visibility on the patient in the absence of a home monitoring system. Further, every physical visit is costly as compared with home monitoring.

Mobility based home monitoring device address these concerns and it will travel with the patient. The mobility device will automatically initiate data transfer at intervals as frequent as the physician may determine. The long range data transmission may be done over a GPRS / 3G network to the backend server from where the physician can view the information using a GUI based application.

The important component the mobile home monitoring solutions lack is intelligent event handling. In many emergency situations the patient may not understand the severity of the issue or be in a position to respond to the issue and physician will also not be continuously monitoring the patient records. This necessitates intelligent event handling to be built in home monitoring solutions.

Event Driven Architecture (EDA) has already proved to be a useful technology in multiple domains to reduce manual intervention and foster a minimal error environment. This paper explores the use of EDA in developing smart mobility solution in patient home monitoring. EDA is helpful as it can trigger intelligent actions as response to events. It can also provide event abstraction for a set of complex events and this can be used to present different set of views to various stake holders in format that is relevant for them.

The proposed solution handles various events types like simple, stream and complex events. Basic rules can be applied on these events and can be used for processing to identify possible risks to patient health. It can be used to provide abstract view of events. The proposed event driven architecture in mobile home monitoring is detailed with use cases of actual scenarios to provide the design logic of the components involved.

The paper is organized as follows:

First a brief description of mobile home monitoring solutions, event driven architecture and algorithms to add intelligence is presented. Proposed event handler and its features are then discussed. Action Handler in the solution is then taken up to define handling of abstraction and health risks. Several use cases are discussed on what scenarios in patient health monitoring can be handled with EDA. The advantages of the approach are then discussed. The different techniques that can used to create advanced smart mobility home monitoring solutions are then briefly covered along with concluding remarks on the possibilities and future research work planned on the subject.

7650-106, Session 11b

Design of effective in-silico adjusting method to support a doctor about the plan of administering medicine

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Based on discrete data of a pain signal f(t) of a patient obtained by observation devices put on the patient, we design observation devices to provide g(t) that cancel f(t) effectively and that is composed by a linear combination of the known time responses hm(t) of the given medicines.

We assume that each observation device is consist of a prescribed sensor and a programmable electric equalizer.

Recently, Kida presents the optimum interpolation approximation of -f(t) that provides the minimum value of various upper limit of many measures of approximation error by using discrete data fm(n*Tm) of output of the given analysis filters.

The optimum interpolation filters that approximate -f(t) from the discrete data fm(n*Tm) are calculated by our theory.

This approximation satisfies a kind of reciprocal theorem that we can exchange the function-forms of the analysis filters and the optimum interpolation filters.

Hence, by considering that the analysis filters and the optimum interpolation filters represent the time responses hm(t) of medicines and the observation devices respectively, we can calculate the optimum characteristics of the equalizer in the observation devices from the given time responses hm(t) of medicines to generate dosage schedules of medicines that make the linear combination of time response hm(t) of dosed medicines cancel f(t).

The outline of the proposed method is as follows:

The pain signal f(t) is generated --> Put observation devices on the patient --> Use the reciprocal theorem to calculate the optimum interpolation filters against the known time responses hm(t) of the medicines --> Program the electric equalizers in the observation devices so that the total characteristics of the observation devices become equal to the optimum interpolation filters --> Get the discrete data fm(n*Tm) by these observation devices --> Calculate g(t), that is quite near to -f(t), that is the sum of products of fm(n*Tm) and hm(t-n*Tm) --> According to g(t) and fm(n*Tm), doctors administer the medicines to cancel f(t).

Please refer to figure published at http://sites.google.com/site/optimumapproximation/poster/Figure1.pdf

7650-107, Session 12

Crack detection in glass plates using nonlinear acoustics with low-profile piezoceramic transducers

R. B. Jenal, W. J. Staszewski, The Univ. of Sheffield (United Kingdom)

Ultrasonic waves are widely used for structural damage detection. Classical approaches based on ultrasonic waves used in Non-Destructive Testing utilise linear amplitude and/or phase variations of reflected, transmitted or scattered waves. Recent years have shown interest in nonlinear vibration and acoustic phenomena for damage detection. A fatigue crack that opens and closes under dynamic loading is most likely the common damage cause of nonlinearity in vibration/modal characteristics. More recently, nonlinear effects have been observed in acoustic waves propagating in structures. Generation of higher harmonics in acoustic signals and modulations of acoustic

signals by vibration are the best known examples. The majority of these applications are in metallic structures.

The paper demonstrates the application of nonlinear acoustics for crack detection in glass plates. The method used is based on various nonlinear phenomena associated with combined ultrasonic wave propagation and modal/vibration excitation. FE analysis is firstly perfomed to establish structural resonances of the analysed glass plate. The crack is introduced to the plate using a Vickers indenter. A low-frequency vibration is applied to a glass plate interrogated with guided ultrasonic waves. This experimental test leads to wave modulation. The presence of modulation indicates damage and the intensity of modulation describes its severity. Surface-bonded, low-profile piezoceramic transducers are used in these investigations allowing for automated on-line monitoring of structural damage.

7650-108, Session 12

Investigation of the threshold behavior of subharmonics for damage detection of a structure with a breathing crack

D. R. Johnson, J. Kim, K. Wang, Univ. of Michigan (United States)

In a previous effort, researchers explored a new methodology for locating a breathing crack in a rod. Excitation of the cracked rod leads to a nonlinear response since the opening and closing of the crack causes the rod stiffness to fluctuate. The response may include subharmonics of the excitation frequency, which can be used to locate the damage along the structure.

A single degree of freedom oscillator model shows a threshold behavior for subharmonic response generation when the stiffness, assumed bilinear, is approximated by a polynomial. Therefore, to ensure a subharmonic response, the interrogation signal should have a proper amplitude and frequency. A finite element model of a cracked rod will verify this threshold behavior condition for a continuous system. Additionally, the relatively large forcing amplitude needed to generate subharmonics may make the large strain nonlinearity significant. Keeping this nonlinearity separate from the crack nonlinearity will be important for accurate localization of the crack.

7650-109, Session 12

Effect of boundary conditions on nonlinear acoustics used for impact damage detection in composite structures

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Non-Destructive Testing based on ultrasonics utilizes various linear elastic wave propagation phenomena for damage detection. In contrast Nonlinear Acoustics uses different types of nonlinear phenomena to detect structural damage. One of the major difficulties associated with this technique is the fact that nonlinearities can be produced not only by damage but also by various intrinsic effects such as material behaviour and/or structural boundary conditions.

The paper investigates the effect of boundary conditions on Nonlinear Acoustics used for damage detection. A simple composite plate with an impact damage is investigated. The plate is clamped using various force levels. The experimental study focuses on the effect of clamping force on various nonlinear phenomena related to propagating acoustical waves. The results demonstrate how important the effect of boundary conditions is when nonlinear acoustics is used for impact damage detection.

7650-110, Session 13

Stress dependent diffuse ultrasonic backscatter coefficient for polycrystalline media

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The diffuse ultrasonic backscatter coefficient (BSC) is a fundamental quantity associated with scattering in heterogeneous media. During a pulse-echo scattering experiment, the energy that scatters back to the source transducer is proportional to the BSC. Theoretical models of the BSC can often be derived from first principles if the heterogeneities can be appropriately modeled. In this case, the statistical properties of the microstructure can be determined in closed form. Polycrystalline materials, such as steel or aluminum, are one class of materials for which the BSC can be determined, typically by assuming that the material is in a stress free state. In this presentation, this fundamental approach is extended to the case in which an applied stress is added to the material. The nonlinear behavior of the grains is included in the analysis such that dependence of the BSC on stress is derived. The stress dependent BSC for different scattering modes relevant to specific experimental configurations is also discussed. Numerical results are presented for materials of common interest and for which single crystal third-order elastic data is available. [Work supported by US FRA]

7650-112, Session 13

Detection and localization of contact-type damages via nonlinear impedance modulation of piezoelectric materials bonded on a beam structure

A. Masuda, J. Aoki, D. Iba, A. Sone, Kyoto Institute of Technology (Japan)

In this paper, a nondestructive, in-service structural integrity monitoring methodology that can detect and characterize local structural damages of contact-type, i.e. damages and failures which come along with generation, growth and/or changes of contacting surfaces, such as cracks, debonding, preload-loss in bolted joints, etc., is presented. The presented monitoring system consists of piezoelectric elements bonded on the structural surface, a high-frequency harmonic voltage source, and a current detector. When the structure is subjected to a dynamic load such as operational load at low-frequencies, it vibrates in the lower vibration modes, and the scattering conditions for the high-frequency elastic waves in the vicinity of the contact-type damages will change in synchronization with the structural vibration because of the fluctuation of the contact conditions. This nonlinear effects of vibro-acoustic interaction between the low-frequency vibration and the high-frequency wave field causes the change in the driving-point impedance of the structure at the high frequency range, which leads to the significant modulation of the coupled electro-mechanical impedance (or admittance) of the piezoelectric elements. Therefore, if the piezoelectric elements are driven by a fixed amplitude high-frequency harmonic voltage source, the nonlinear modulation of the coupled admittance can be observed as the amplitude and phase modulation of the current flowing through the piezoelectric element. A modeling and analytical study of the nonlinear piezoelectric impedance modulation is presented in the case of single mode excitation both in quasi-static and dynamic conditions. A damage evaluation measure independent of the amplitude of pump excitation is proposed based on the dimensionless modal stiffness fluctuation estimated from the instantaneous admittance reconstructed from the demodulated current responses. Furthermore, a fundamental strategy of damage localization based on the nonlinear acoustic modulation is constructed based on the concept of demodulated wave field. Experiments using a cracked beam are conducted to examine the performance of the proposed techniques.

7650-113, Session 13

Dynamics characterization and health monitoring of membrane structures by time-frequency analysis

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Membrane dynamics is often nonlinear and nonstationary because of geometric nonlinearity induced by high local flexibility, non-uniform pre-tension, light weight, dynamic coupling with surrounding air, wave propagation, support-induced nonlinearity, and others. Hence, dynamics characterization and health monitoring of membrane structures requires advanced time-frequency analysis, and the focus is on how to obtain accurate time-varying frequency and amplitude of a nonlinear nonstationary signal. Here we propose the use of a conjugate-pair decomposition (CPD) method with the empirical mode decomposition (EMD) for characterization of membrane dynamics. First, EMD with signal conditioning techniques is used to separate a compound membrane response into well-behaved intrinsic mode functions (IMFs) without assuming the signal to be harmonic. Then, a pair of sliding conjugate functions is used to accurately extract the time-varying frequency and amplitude of each IMF by using only three neighboring data points for each time instant. Because the variations of frequencies and amplitudes of IMFs contain system characteristics, they can be used for system identification and damage detection. Several discrete systems' simulated responses are used to validate CPD's accuracy and capability for system identification and health monitoring. The results are also compared with those from Hilbert-Huang transform (HHT). It shows that the frequencies and amplitudes tracked by CPD have about the same accuracy as those extracted by HHT but without the edge effect that HHT suffers from. Experimental nonlinear responses of a horizontally tensioned Kapton membrane subjected to a transverse harmonic excitation provided by a shaker at one end are used to validate the proposed methodology. Results show that the clamped-clamped supports and pre-tension cause the first-mode vibration to have a hardening cubic nonlinearity, and several other nonlinear phenomena are identified.

7650-114, Session 14

Autofocus for sparse array imaging

A. J. Croxford, A. J. Hunter, Univ. of Bristol (United Kingdom)

Significant research effort has been put into developing permanently attached sparse array networks. It is envisaged that such networks can be used to monitor the state of a complete structure over time. If such a system is applied to an existing structure it is likely that the large areas of structure that will need to be instrumented will result in significant errors in the location of transducers. This has the potential to adversely affect the ability of a sensor network to detect the presence of a defect or misclassify detected features. This paper addresses this problem, presenting an autofocus approach to correct errors in the experimental parameters, including transducer locations, group velocity and electronic delay. The technique makes use of the first ultrasonic arrival as an error metric and alters the parameter values to minimise this metric. The improvements that the autofocus produce on the resulting defect detection are shown clearly indicating an improvement in the point spread function. In addition the ability of the technique to correct the parameters for complex geometries is illustrated.

7650-115, Session 14

Efficient data capture and post-processing for real-time imaging using an ultrasonic array

L. Moreau, A. J. Hunter, P. D. Wilcox, B. W. Drinkwater, Univ. of Bristol (United Kingdom)

Over the past few years, ultrasonic phased arrays have shown good potential for non-destructive testing (NDT), thanks to high resolution imaging algorithms that allow the characterization of defects in a structure. Many algorithms are based on the full matrix capture, obtained by firing each element of an ultrasonic array independently, while collecting the data with all elements. Because of the finite sound velocity in the specimen, two consecutive firings must be separated by a minimum time interval. Therefore, more elements in the array require longer data acquisition times. Moreover, if the array has N elements, then the full matrix contains N*N temporal signals to be processed. Because of the limited calculation speed of current computers, a large matrix of data can result in rather long post-processing times. In an industrial context where real-time imaging is desirable, it is crucial to reduce acquisition and/or post-processing times. This paper investigates methods designed to reduce acquisition and post-processing times for the TFM and wavenumber algorithms. To reduce data capture and post-processing, limited transmission cycles are used. Post-processing times is also further reduced by demodulating the data to baseband, which allows reducing the sampling rate of signals. Results are presented so that a compromise can be made between acquisition time, post-processing time and image quality. Possible improvement of images quality, using the effective aperture theory, is discussed. This has been implemented for the TFM but it still has to be developed for the wavenumber algorithm.

7650-116, Session 14

Structural health monitoring of an impulsively loaded structure using wave-propagation based instantaneous baseline

J. C. Dodson, Virginia Polytechnic Institute and State Univ. (United States); J. R. Foley, Air Force Research Lab. (United States); D. J. Inman, Sr., Virginia Polytechnic Institute and State Univ. (United States)

Recent advances in Structural Health Monitoring have provided the means of eliminating the prerecorded baseline measurement by producing an instantaneous baseline. The damage detection method presented is an extension of an existing near-real time damage detection instantaneous baseline method by using ambient impact and passive sensing in the place of the pitch-catch technique. The method uses an array sensors and compares the features in the data of the different wave-propagation paths to determine an undamaged baseline. The wave-propagation paths that greatly differ from the instantaneous baseline indicate the location of damage. The extended instantaneous baseline method using passive sensors and ambient excitation are presented, including details of the signal processing algorithm and evaluation of the method for detecting various types of damage.

7650-117, Session 14

Immune-inspired sensor network fault detection and self-healing

B. Chen, C. Zang, Michigan Technological Univ. (United States)

The reliability of monitoring sensor networks is directly affected by sensor faults. The possibility of sensor fault adds an additional layer of complexity to the structure damage detection problem since it is difficult to distinguish that the change of sensor data is due to sensor fault or structure damage. To address this challenging problem, this paper proposes an immune-inspired approach for sensor network fault detection and self-healing.

The presented fault detection and self-healing method consists of three stages: fault detection, fault tolerance, and fault isolation (self-healing). The negative selection algorithm inspired by immune self/nonself discrimination principle is used for initial detection of sensor fault. The detected faulty sensor is confirmed by examining the measurements of other sensors in the same group. Fault tolerance stage is used to deal with temporal fault. In this stage, the centroid of the self-set is used to replace the sensor measurement for the structure damage classification. If a sensor is continuously identified as a faulty sensor, the system will finally isolate this faulty sensor by excluding the measurement of the sensor in decision making.

The integration of fault detection with fault tolerance and fault isolation (self-healing) through a coordinated response allows SHM sensor networks to deal with faulty sensors at a system-level. The presented approach has been tested using experimental data of a benchmark civil structure. The self/nonself is determined by the affinity between the test data and the members in the self-set.

7650-118, Session 14

Combined distributed and concentrated transducer network for failure indication

W. M. Ostachowicz, Gdynia Maritime Academy (Poland); T. Wandowski, P. Malinowski, Polska Akademia Nauk (Poland)

In this paper algorithm for discontinuities localisation in thin panels manufactured of aluminium alloy has been proposed. Above mentioned algorithm uses Lamb wave propagation methods for failure localisation. Elastic waves have been generated and received using piezoelectric transducers. They have been arranged in concentrated arrays that are distributed on the specimen surface. In this way almost whole specimen could be monitored using this combined distributed and concentrated transducer network. Excited elastic waves propagate and reflect from panel boundaries and discontinuities existing in the panel. Wave reflections have been registered through the piezoelectric transducers and later used in signal processing algorithm. Proposed processing algorithm consists of two parts: signal filtering and extraction of failures locations. The first part has been used in order to enhance signals by removing noise from them. Second part allowed to extract features connected with wave reflections from discontinuities. Based on extracted features the damage influence maps have been created. Damage maps indicate intensity of elastic wave reflections which correspond to failures coordinates. Described signal processing algorithms have been implemented in the MATLAB® environment. It should be underlined that results in this work have been only based on experimental signals.

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