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2014 Smart Structures/NDE

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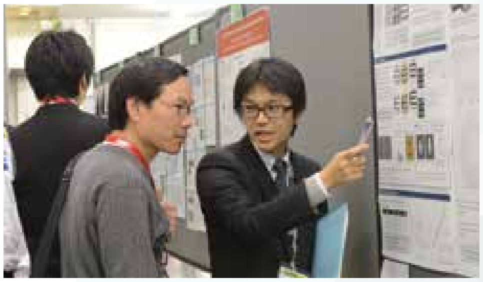

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SPIE would like to express its deepest appreciation to the symposium chairs, conference chairs, program committees, session chairs, and authors who have so generously given their time and advice to make this symposium possible.

The symposium, like our other conferences and activities, would not be possible without the dedicated contribution of our participants and members. This program is based on commitments received up to the time of publication and is subject to change without notice.

Conference 9055: Bioinspiration, Biomimetics, and Bioreplication IV

Sunday - Wednesday 9 –12 March 2014

Part of Proceedings of SPIE Vol. 9055 Bioinspiration, Biomimetics, and Bioreplication 2014

9055-1

A future of living machines?: International trends and prospects in biomimetic and biohybrid systems *(Keynote Presentation)*

Tony J. Prescott, Nathan Lepora, The Univ. of Sheffield (United Kingdom); Paul F. M. J. Vershure, Univ. Pompeu Fabra (Spain)

Research in the fields of biomimetic and biohybrid systems is developing at an accelerating rate. Biomimetics can be understood as the development of new technologies using principles abstracted from the study of biological systems, however, biomimetics can also be viewed from an alternate perspective as an important methodology for improving our understanding of the world we live in and of ourselves as biological organisms. A biohybrid entity comprises at least one artificial (engineered) component combined with a biological one. With technologies such as microscale mobile computing, prosthetics and implants, humankind is moving towards a more biohybrid future in which biomimetics helps us to engineer biocompatible technologies. This talk will review recent progress in the development of biomimetic and biohybrid systems focusing particularly on technologies that emulate living organisms—living machines. Based on our recent bibliographic analysis (Lepora et al., Bioinspiration and Biomimetics, 2013) we will examine how biomimetics is already creating life-like robots and identify some key unresolved challenges that constitute bottlenecks for the field. Drawing on our recent research in biomimetic mammalian robots, including humanoids, we will review the future prospects for such machines and consider some of their likely impacts on society, including the existential risk of creating artefacts with significant autonomy that could come to match or exceed humankind in intelligence. We will conclude that living machines are more likely to be a benefit than a threat but that we should also ensure that progress in biomimetics and biohybrid systems is made with broad societal consent.

9055-2

Including natural systems into the system engineering process: benefits to spaceflight and beyond *(Invited Paper)*

George Studor, NASA Johnson Space Ctr., Retired (United States)

What self-respecting Systems Engineering team lead dares ask the question “What can we learn from Nature that will help us solve our challenge?” For that matter, who is on the SE team is charged with or capable of answering that question? And why bother investigating Nature at all? Don’t most of the practical uses of natural, living and non-living, creations happen in a fairly seredipity way? - novel solution looking for an application? If I am the scientist studying nature, how can I know if any of it matters to a technologist or engineer? If it does matter, how do I know what to study and test and how to make it widely know to that engineering world? This topic will tackle the next step beyond bioinspiration... that is, the systemmatic inclusion of natural, living and non-living, things and functions in the standard process of system engineering and technology development. We will look at the questions above and also answer - “why now?”. We will look at the changing the customer - supplier relationships between science and engineering, an inevitable consequence of our knowledge of and ability to replicate or mimick more and more of nature. Finally, we will look at several examples of how the process might be incrementally applied to the needs of human and robotic spaceflight missions and challenges such as walking in space with two hands free, inspecting difficult to access areas, autonomous inspection, designing an antenna, capturing an asteriod and engineering complex remote space habitats. We will also expose you to what is going on through the INCOSE Natural Systems Working Group and NASA’s Engineering and Safety Center(NESC) Robotic Spacecraft Technical Discipline Team efforts in this area.

9055-3

Resonance versus aerodynamics for energy savings in agile natural flyers

Javaan S. Chahl, Univ. of South Australia (Australia) and Defence Science and Technology Organisation (Australia); Jia M. Kok, Univ. of South Australia (Australia)

Insects are the most diverse natural flyers, being able to hover and perform agile maneuvers. Dragonflies in particular are one of the most aggressive flyers, attaining accelerations of up to 4g. Flight of all insects requires that demanding aerodynamic and inertial flapping loads are overcome. It has been proposed that the use of resonance is a primary driver in reducing energy costs associated with hover, by storing energy in an elastic thorax/musculature/connective tissue and releasing it on the following half-stroke. Certainly for insects dominated by inertial loads, such a mechanism would be extremely beneficial. However in highly maneuverable, aerodynamically dominated flyers, such as the dragonfly, the use of elastic storage members requires further investigation.

We show that employing resonant mechanisms in a real world configuration produces energy savings of 6% that is further reduced by 50 – 133% across the operational flapping frequency band of the dragonfly. Using the simple harmonic analysis to represent the dynamics of a dragonfly, we further demonstrate a reduction in maneuvering limits of 2 to 4 times for a system employing elastic mechanisms. This is in contrast to the potential energy savings from regulating aerodynamics via active wing articulation which is approximately 28 to 50%. Additionally, this method of energy savings provides flexibility between an energy efficient hover state and a maneuverable state capable of large accelerations. We conclude that active wing articulation is preferable to resonant mechanisms for aerodynamically dominated natural flyers.

9055-4

Designing nanomanufacturing system from laboratory based nano-fab operation *(Invited Paper)*

Tarun Gupta, Western Michigan Univ. (United States)

This paper outlines four most significant aspects of the nanomanufacturing process when considering scaling up a nano-fabrication process into a commercialized version for high volume production of a nano-scale feature based product. The four aspects are abundance of nanomaterials, fabrication & production process, characterization & performance measurement; and finally the emerging markets for nanoscale products. As far as addressing the abundant need for nanomaterials is concerned several researching institutions and federal agencies are engaged in synthesizing and characterizing newer materials to create specific alternative nanomaterials for scalable nanomanufacturing.

The second aspect for sustainable nanomanufacturing is a reliable, repeatable and stable process of manufacturing. To this effect recent discovery of growing single walled carbon nanotubes (SWCNT) with not only a desired attribute but also with desired size – length & diameter have now been claimed to be achieved by controlling atomic structure using chirality-controlled synthesis with vapor-phase epitaxy for SWCNT during the growth process. Nano-ink process is another example of highly repeatable & consistent nanomanufacturing process.

The third aspect for sustainable nanomanufacturing is for characterization and performance measurement has also experienced growth with enhancement to speed, accuracy & precision in the steps involved. Conducting these measurement inline in a high speed scaled-up production system is another issue that is yet to be addressed and thus needs special attention.

The fourth aspect for sustainable scaleable nanomanufacturing is the emerging markets looking for solving various chronic problems such as recurring losses in airline, automotive and sporting goods industry for example.

9055-5

Simple mass-fabrication method of micro-color-powders based on the Morpho butterfly's blue for wide applications

Akira Saito, Osaka Univ. (Japan) and Japan Synchrotron Radiation Research Institute (Japan); Kosei Ishibashi, Takuto Shibuya, Megumi Akai-Kasaya, Yuji Kuwahara, Osaka Univ. (Japan)

Morpho butterfly's brilliant blue is well known as an example of the structural color and attracts interest due to a metallic luster from the biological body. The blue is produced by pigment-free protein on their scales. The origin of the color with high reflectance (> ~60%) is then attributed to an interference from a periodic microstructure. However, the blue in too wide angle (> ± 40° from the normal) contradicts the interference. This mystery has been clarified by a specific nanostructure having nano-disorder preventing the rainbow color. This principle has been proved successfully by emulating the 3D nanostructures composed by multilayer film deposited on a nano-patterned substrate containing specific disorders. Such specific structural color has recently been found to have wide potential applications. However, for true applications, we needed various steps to develop: 1) mass-production, 2) control of optical properties, 3) simulation of spectra from the nano-randomness, etc. The remaining key issue is to produce the micro-powders of the color materials, because all processes have long been accompanied with the thick substrate designed with a specific nano-disorder, which has limited fatally the variety of applications. Thus, we developed a new and quite simple process to mass-fabricate the Morpho-color powders maintaining the specific properties in a tiny size. This process will extend effectively the applications of the specific color, which can enable the Morpho-coloring without any limit of the shape.

9055-6

Fine-scale features on bioreplicated decoys of the emerald ash borer provide necessary visual verisimilitude

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The emerald ash borer (EAB), Agrilus planipennis, is an invasive tree-killing pest in North America. Like other buprestid beetles, it has an iridescent coloring, produced by a periodically layered cuticle that reflects light at 590 nm wavelength. The males perform a visuallymediated ritualistic mating flight directly onto females poised on sunlit leaves. We attempted to evoke this behavior using artificial visual decoys of three types. To fabricate decoys of the first type, a PET sheet coated with a Bragg-stack reflector was loosely stamped by a bioreplicating die. For decoys of the second type, a green-painted PET sheet was heavily stamped by the same die. Every decoy of these two types had an underlying black absorber layer. Decoys of the third type were produced by a rapid prototyping machine and painted green. Fine-scale features were absent on the third type. Experiments were performed in an American ash forest infested with EAB, and a European oak forest home to a similar pest, the European oak borer (EOB), Agrilus biguttatus. When pinned to leaves, dead EAB females, dead EOB females, and bioreplicated decoys of both types often evoked the complete ritualized flight behavior. Males also initiated approaches to the rapidly prototyped decoy, but would divert elsewhere without making contact. The attraction of the bioreplicated decoys was also demonstrated by providing a high dc voltage across the decoys that stunned and killed approaching beetles. Thus, true bioreplication with fine-scale features is necessary to fully evoke ritualized visual responses in insects, and provides an opportunity for developing insect-trapping technologies.

9055-7

Fabrication of biomimetic hierarchical microstructures by using self-organization processes

Aki Sato, Yuji Hirai, Chitose Institute of Science and Technology (Japan); Yoshimitsu Matsunaga, Tohoku Univ. (Japan); Takuya Ohzono, Masatsugu Shimomura, National Institute of Advanced Industrial Science and Technology (Japan)

Superhydrophobic surfaces have attracted attention due to their possibilities of self-cleaning surfaces, anti-fouling surfaces and so on. A great number of research focuses on fabrication of microstructures and the correlations between microstructure and wettability[1]. We have reported that honeycomb-patterned porous polymer films can be prepared by casting a solution of a hydrophobic polymer and an amphiphilic copolymer on a solid substrate by using condensed water droplet arrays as templates. Superhydrophobic pincushion films can be also obtained by peeling off the surface structures of honeycomb-patterned films [2]. Furthermore, it is well known that self-organized winkle structures are the deformable anisotropic microstructure [3]. In this report, we show the preparation of the hierarchically structured anisotropic superhydrophobic surface by combinations of pincushion films and wrinkle structures. We prepared honeycomb-patterned films by simple casting method. A Polyimide film and honeycomb film were fixed on Polydimethylesiloxan (PDMS) by using glue, after peeling off the surface structures of honeycomb-patterned films, superhydrophobic pincushion films were formed. When the samples were applied in plane compressive stress, sub-mm scale buckling (wrinkle structure) were formed at the surface. The wrinkle structure were reversed by releasing external compressive stress. As results, hierarchical pincushion and wrinkle structures were obtained. The surface wettability of the sample will be discussed.

[1] F. Xia and L. Jiang, adv. , 2008, 9999, 1-7

[2] H. Yabu, Y.Hirai, M. Shimomura. Langmuir, 2006, 22(23),9760-9764

[3] T. Ohzono and M. Shimomura, Phys. Rev. B, 2004, 69(13), 132202-132206

9055-8

Noise-driven signal transmission device using molecular dynamics of organic polymers

Naoki Asakawa, Gunma Univ. (Japan); Teruo Kanki, Hidekazu

Tanaka, Osaka Univ. (Japan)

Neuro-inspired stochastic threshold units could be potential key devices for noise-driven sensors and information processors with low energy consumption. The fluctuation of electric conductivity near trap-filling transition under space charge limited conduction in disordered solids is conventionally one of unwanted factors that discourage from the realization of high performance polymer electronics devices. Contrary to the conventional point of view, the fluctuation of conduction could be useful to mimick quasi-stochastic nature of electric property of a neuron. Here, we fabricated neuro-inspired stochastic threshold units using the trap filling transition coupled with molecular dynamics in poly(3-alkylthiophene)s [P3ATs]. This presentation deals with variable-temperature direct current conductivity for vertical-type device elements of Au/poly(3-decylthiophene)[P3DT](thickness:100nm)/Au, which show multiple conducting states and quasi-stochastic transitions between these states. Noise measurements indicate the omega^{-2}-type (if V < V_{TFT}=10V) and omega^{-1}-type (if V > V_{TFT}) power spectral densities, where V and V_{TFT} are an applied voltage and the voltage for trap-filling transition(TFT), respectively. The noise generation is due to the TFT in association with tilt dynamics of thiophene rings in pi-conjugated polymers near the order-disorder phase transition. At 298K, the quasi-stochastic behavior is more noticeable for P3DT than poly(3-hexylthiophene).

9055-9

Bio-mimetic optical sensor for structural deflection measurement

Susan A. Frost, NASA Ames Research Ctr. (United States); Robert Streeter, Cameron H. G. Wright, Steven F. Barrett, Univ. of Wyoming (United States)

Research at NASA focused on reducing the environmental impact of aviation depends on accurate wing deformation measurements to enable safe and efficient operation of new aircraft configurations. Existing sensor solutions, such as strain gauges, are hindered by high computational requirements. A bio-mimetic vision sensor (based on Musca domestica, the common house fly) for detecting aircraft wing deformation is described. The sensor is a very small, low power device that makes use of revolutionary optical sensor design resulting in significantly improved motion detection capabilities when compared with conventional optical sensors. The simple analog architecture allows for real-time solution at any desired bandwidth to enable accurate measurement of structural bending deflection.

While much of the work to date on compound insect eye based sensors has focused on the apposition compound eye, the neural superposition compound eye has been the basis for previous research by the authors. This paper describes extensions to previous work to create a sensor that includes groupings of photoreceptors with seven parallel optical axes and seven partially overlapping Gaussian response curves. The signals from the six photoreceptors in the “outer ring” of a group are combined using signal routing and analog preprocessing circuitry to create the bio-mimetic equivalent of the laminal cartridge. Any arbitrary number of these artificial ommatidia can be combined to create the desired sensor characteristics for the application. The proposed sensor takes advantage of the motion hyper-acuity inherent in its design to detect extremely small motions, thereby enabling structural deflection measurements.

9055-10

Optical flow on a linear compound array

Javaan S. Chahl, Univ. of South Australia (Australia) and Defence Science and Technology Organisation (Australia)

Most imaging arrays capture light from a continuously varying direction in space. The compound eye of the insect in its simplest concept creates an image from environment across a solid angle. A pinhole camera produces an image of a solid angle such that straight lines in space are captured as straight lines on the image plane. Yet insect compound eyes do not have all of their optical axes arranged evenly across a spherical surface. Many insects have a foveal area in frontal part of the eye in which optical axes of adjacent ommatidia are almost parallel.

We have examined the optical flow properties of linear optical arrays in which all optical axes are parallel. Such “paraxial” arrays have unusual properties, in many regards being the complement of their angular projection counterparts. A paraxial array directly measures the speed of translation orthogonal to the optical axes as linear optical flow. More surprisingly, a paraxial array, when rotated, detects range as a ratio of optical flow and angular velocity. Thus for a fixed angle of rotation, optical flow is directly proportional to the range to the object being imaged.

A series of experiments was conducted to demonstrate the viability of the device as an instrument for measuring range and egomotion. Precision motion control and an adjustable paraxial imaging device was used to measure sampling parameter sensitivity. In realistic scenes, accuracy of the order of 10% was achieved for range and better than 5% for egomotion.

9055-11

Whisker-like sensors with tunable follicle sinus complex for underwater applications

Pablo Valdivia y Alvarado, Singapore-MIT Alliance (Singapore) and Massachusetts Institute of Technology (United States); Karthik Srivatsa, SMART-Singapore MIT Alliance for Research & Technology (Singapore)

In this study we present the design, analysis, and experimental validation of a follicle-sinus complex (FSC) unit for whisker-like sensors. The FSC unit displays variable visco-elasticity enabled by a dielectric elastomer (DE) mechanism. Our previous studies on whisker-like sensors for underwater applications have shown the dependence between sensor performance and FSC material properties. Both static and dynamic sensor measurements are heavily influenced by FSC viscoelasticity. Variations in FSC modulus of elasticity and viscosity affect the sensitivity and range of sensors as the fluid-structure interactions between the environment flow disturbances and the sensors whisker-like shaft are affected by the boundary conditions provided by FSCs. A new FSC design is presented using a DE mechanism to tune the material properties of the follicle region. A model is described to better predict sensitivity and measurement range characteristics from sensor geometric and DE parameters. The model accounts for the viscoelastic and dielectric properties of the FSC components, pre-loading of the FSK volume, and stiffness ratios between the sensor whisker-like shaft and the FSC region.

To verify model predictions two experiments are described and the results presented. The natural frequencies of the whisker-like sensors are characterized experimentally using impulse tests and compared with model estimates. In addition, sensitivity to different ranges of flow disturbance and effective measurement range are measured in a towing tank. Results for a whisker-like sensor prototype are summarized and discussed.

9055-12

Role of the array geometry in multi-bilayer hair cell sensors

Nima Tamaddoni, Stephen A. Sarles, The Univ. of Tennessee (United States)

Recently, a bio-inspired synthetic membrane-based hair cell sensor has been fabricated and characterized. This sensor generates current in response to perturbing stimuli, such as airflow or free vibration. Vibration transferred from the hair to the bilayer causes a voltage-dependent time rate of change in electrical capacitance of the membrane, which produces measurable current. Studies to date have been performed on systems containing only two droplets and a single membrane, although it has yet to be determined if a biomimetic array of hair cells can enable increased sensitivity, improved directionality, and a wider frequency range of operation. The fact that the lipid bilayer in this sensor provides mechanoelectrical transduction of hair motion suggests that both the mechanical and electrical responses of a sensor array may be greatly affected by the geometric arrangement of droplets and interfacial bilayers. Two specific questions that arise in considering how to construct multi-bilayer arrays include: 1) How do additional droplets affect the propagation of vibrational energy across multiple bilayer interfaces? 2) How do additional capacitances in the system from the added bilayers contribute to the measured sensing currents and affect the placement of sensing electrodes? To answer these questions, we will experimentally study arrays of 3-5 droplets that feature a minimum of 2 bilayers. For various geometric configurations of droplets and positions of sensing electrodes, we will measure the vibration-induced currents across all bilayers in the network to study how mechanical boundary conditions and equivalent capacitance of the array affects the sensing response.

9055-13

Towards a fish-inspired underwater hearing device

Tony C. H. Tse, John Montgomery, Iain A. Anderson, The Univ. of Auckland (New Zealand)

In the underwater world, sound provides important environment clues for survival and orientation. Naturally, fishes have adapted to hearing underwater. They are able to hear with respectable sensitivity from infra-sound to thousands of hertz and more importantly, localise sound with great accuracy. These feats are remarkable given the simplicity of the fish's hearing organ and its small size in comparison to the acoustic wave length.

We draw inspiration from the fish "hearing" organ, the otolith, to create a portable engineering device that can augment a human diver's ability to hear underwater. The otolith is an inertial displacement sensor, consisting of a dense bony mass that acts as a reference to the surrounding sensory hair cells. Under the influence of an acoustic wave, the sensory hair cells are displaced relative to the mass. The relative displacement is very small, close to 0.1nm at the fish hearing threshold.

One of the challenges in making the fish hearing device a reality lies in being able to sense the small relative displacement. For this we are exploring the use of capacitive sensing, in a device with high resolution, compactness and good noise performance. In this paper, we present the obstacles encountered and a computer model that can be used to optimise the hearing sensor's design.

9055-14

Self-organization and motion in plants *(Invited Paper)*

Torben A. Lenau, Technical Univ. of Denmark (Denmark); Thomas Hesselberg, Univ. of Oxford (United Kingdom)

Self-organization appeal to humans because difficult and repeated actions can be avoided through automation via bottom-up nonhierarchical processes. This is in contrast to the top-level controlled action strategy normally applied in automated products and in manufacturing. There are many situations where it is required that objects perform an action dependent on external stimuli. An example is automatic window blinds that open or closes in response to sunlight level. However, simpler and more robust designs could be made using the self-organizing principles for movement found in many plants. Plants move to adopt to external conditions, e.g. sun-flower buds tracking the sun, touch-me-not Mimosa pudica and venus fly traps Dionaea muscipula when touched upon and evening primrose Oenothera biennis that opens at precise hours in the evening. The paper describes work done on mimicking the way these plants registers the external stimuli and transforms that into an mechanical action.

9055-15

Kirigami design and fabrication for biomimetic robotics *(Invited Paper)*

Jonathan M. Rossiter, Sina Sareh, King's College London (United Kingdom)

Biomimetics faces a continual challenge of how to bridge the gap between what Nature has so effectively evolved and the current tools and materials that we, as engineers and scientists, can exploit. Kirigami, from the Japanese 'cut' and 'paper', is a method of design where laminar materials are cut and then forced out-of-plane to yield 3D structures. Kirigami design provides a convenient and relatively closed design space within which to replicate some of the most interesting niche biological mechanisms. These include complex flexing organelles such as cilia in algae, energy storage and buckled structures in plants, and organic appendages that actuate out-of-plane such as the myoneme of the Vorticella protozoa. Where traditional kirigami employs passive materials which must be forces to transition to higher dimensions, we can exploit planar smart actuators and artificial muscles to create self-actuating kirigami structures. Here we review biomimetics with respect to the kirigami design and fabrication methods and examine how smart materials, including electroactive polymers and shape memory polymers, can be used to realise effective biomimetic components for robotic, deployable structures and engineering systems. One-way actuation, for example using shape memory polymers, can yield complete self-deploying structures. Bi-directional actuation, in contrast, can be exploited to mimic fundamental biological mechanisms such as thrust generation and fluid control. We present recent examples of kirigami robotic mechanisms and actuators and discuss planar fabrication methods, including rapid prototyping and 3D printing, and how current technologies, and their limitations, affect Kirigami robotics.

9055-16

Design and gait analysis of a multi-segment in-pipe robot inspired by earthworm's peristaltic locomotion

Hongbin Fang, Univ. of Michigan (United States) and Tongji Univ. (China); Chenghao Wang, Suyi Li, Kon-Well Wang, Univ. of Michigan (United States); Jian Xu, Tongji Univ. (China)

Peristalsis is an advanced form of terrestrial locomotion and is also the dominant way of burrowing through substrate for some soft-bodied animals. Earthworm is a typical example of metameric worm that uses retrograde peristalsis waves to achieve locomotion. This study reports experimental progress towards the development of a multi-segment in-pipe robot inspired by earthworm's body structure and locomotion mechanism. In addition to the robot prototyping, another area of interest in our investigation is the correlation between gait design and locomotion characteristics. To mimic the alternating contraction and elongation of a single earthworm's segment, a robust actuation mechanism employing servomotor is developed. In each segment (actuator) of the robot, servomotor-driven cords and passive spring steel belts are used to imitate the earthworm's longitudinal and circular muscles, respectively. Experimentally, the axial and radial deformation of the actuator is measured and it agrees with the theoretical predictions. Based on the principle of retrograde peristalsis wave, a gait generation algorithm is put forward for the multi-segment robot, following which, gaits of the robot can be constructed. Employing the designed actuators, an eight-segment earthworm-like robot prototype is presented in this paper, which can effectively achieve both horizontal and vertical locomotion in pipes. By changing gait parameters, i.e., by different gaits, locomotion characteristics such as average speed, load capacity and anchor slippage can be significantly tailored, which qualitatively agrees with the theoretical analysis. The proposed actuation method and prototype of in-pipe robot provide a bionic realization of earthworm's locomotion with promising application in pipeline inspection and cleaning, and even in human's GI tract examination if it can be minimized.

9055-17

Fish-robot interactions in a free-swimming environment: effects of speed and configuration of robots on live fish

Sachit Butail, Giovanni Polverino, Paul T. Phamduy, Fausto Del Sette, Maurizio Porfiri, Polytechnic Institute of New York Univ. (United States)

The possibility of modulating the behavior of live fish through the use of autonomous robots has several advantages in both biology and engineering. In biological applications, the controllability and repeatability of robotic stimuli can be used to elicit meaningful and consistent responses in experimental subjects to improve our understanding of the fundamental principles of social behavior. Additionally, robots can be used to attract or repel target species for possible use in animal control and preservation strategies as well as fish aquaculture. In this work, we explore the feasibility of regulating animal behavior with free-swimming robotic fish. In a comprehensive experimental study, we systematically vary the speed, number of robots, and their relative configuration as they swim in circular trajectories within a large square tank. The robots are designed to present known visual features of attraction in zebrafish including enhanced coloration, aspect ratio of a fertile female, and carangiform/subcarangiform locomotion, and are controlled autonomously with the help of an online multi-target tracking system. When multiple fish are present with a single robot, the resulting trajectory data shows that the speed of the robot is a determinant of group cohesion, which increases with the speed of the robot until it reaches 3 cm/s. When multiple robots interact with a single fish, the distance of the fish to a robot is significantly affected by the configuration of the robots, with the most time spent in a robot's proximity when they are swimming far from each other.

9055-43

Influence of shunt-damping circuit on the dynamic response of a bio-inspired piezoelectric micro-pillar sensor

Junliang Tao, The Univ. of Akron (United States); Xiong Yu, Case Western Reserve Univ. (United States)

A novel hair flow sensor is designed inspired by the superficial neuromasts in the lateral line system of fish. The transduction element of the hair sensor is a piezoelectric fiber with a pair of electrodes on the surface of the fiber. The hair sensor is proved to have good linearity and directional sensitivity, which are the key sensing characteristics of the biological hair cell. To improve the flexibility and strength of the sensor, the piezoelectric fiber is embedded into a micro-scale host cylinder.

The dynamic response of the sensor is critical for flow sensing applications. Traditional methods to modify a sensor's frequency response (e.g., attaching a mass to the sensor or altering the geometry of the sensor) are challenging to apply in the micro-scale (Figure 1a). An innovative approach is explored inspired by the shunt circuit damper, usually seen in the damping control of structures. By connecting the piezoelectric sensor to an external circuit, part of energy generated due to the vibration of the sensor would dissipate through the shunt circuit (Figure 1a). This method is often used to increase the damping of vibrating structures. The influence of shunt-damping circuit on the dynamic response of the novel hair sensor is evaluated in this study. Finite Element Method is used to study the response of this complex system, which involves the coupling of the structural dynamic response, the piezoelectric response, and the circuit response. This is implemented in a multiphysics-software COMSOL®.

The effects of components of the external circuit (i.e., resistor R and inductor L) were evaluated. It was found the presence of the circuit would significantly influence the dynamic response of the hair sensor. On the one hand, the circuit would decrease the resonance response, or induce extra damping to the system; on the other hand, it would slightly shift the resonance frequency and significantly increase the bandwidth of the sensor (Figure 1b), which is desirable for flow sensing. It was found that optimal values for the R and L exist for maximum bandwidth. The optimal resistance and inductance was determined through the above-mentioned numerical model. The dynamic responses of sensors with different host materials and corresponding optimal external circuits were also studied and compared, in order to achieve optimal design of the sensor.

9055-19

Wood as inspiration for new stimuli-responsive structures and materials *(Invited Paper)*

Joseph E. Jakes, Sam L. Zelinka, U.S. Forest Service (United States); Nayomi Plaza, U.S. Forest Service (United States) and Univ. of Wisconsin-Madison (United States); Don Stone, Univ. of Wisconsin-Madison (United States); Sophie C. Gleber, Stefan Vogt, Argonne National Lab. (United States)

New stimuli-responsive structures and materials are being pursued in areas as diverse as medical devices, deployable space structures, energy harvesting, sensors, and artificial muscles. Despite the long history of wood science research, wood continues to provide new inspiration for biomimetic structures and materials. Our recent discoveries include the inspiration for a high specific torque microactuator with shape memory capabilities and a stimuli-responsive material for chemical transport. We find wood slivers twist multiple revolutions per cm length when wetted. The majority of that twist can be locked in by drying under constraint, and then the locked-in twist can be recovered by rewetting the bundle. On a torque to mass ratio, the torque generated during twisting is higher than an electric motor. Furthermore, using the high spatial resolution and sensitivity of x-ray fluorescence microscopy (XFM) at beamline 2-ID-E at the Advanced Photon Source at Argonne National Laboratory we recently discovered a moisture content threshold for ionic diffusion through wood cell walls. XFM was used to map out metal ions deposited into individual wood cell walls. Then, using a relative humidity (RH) chamber custom built for beamline 2-ID-E the diffusion of the metal ions was observed in situ at increasingly higher RH. It was found that ions did not diffuse through wood cell walls until approximately 80% RH. We propose that both the shape memory twist effect and the moisture content threshold for ionic diffusion are controlled by the hemicelluloses passing through a moisture-dependent glass transition at approximately 80% RH.

9055-20

Enzyme mimetic bioinorganic nanoparticles: tuning, inhibiting, and restoring of catalytic activities

Mato Knez, CIC nanoGUNE Consolider (Spain) and Ikerbasque (Spain); Lianbing Zhang, Le Li, Unai Carmona, CIC nanoGUNE Consolider (Spain)

Apoferritin it is a spherical protein complex with a hollow inner cavity. It is an active cellular protein with intrinsic impact on the iron metabolism and oxidative stress regulation and shows specific enzymatic activities. Due to its structural features it is a widely used protein template for the synthesis of various nanomaterials with promising application potential. The well-characterized enzyme mimetic catalase and superoxide dismutase (SOD) activities of metal-NPs were used for further inhibition analysis with typical reaction specific and unspecific inhibitors.

As a result we found that the enzyme mimetic activities of ferritin-encapsulated metal nanoparticles can be inhibited with inhibitors typically active with biological enzymes. In some cases the inhibition affected only one enzyme mimetic activity, while in other cases multiple catalytic activities were inhibited, indicating the possibility to achieve selective and specific activity suppression. This opens the door towards controlling the activities of NPs in a reaction specific manner with further inhibitor screening, which is greatly interesting for NP engineering targeting enzyme mimetics. Restoring the chemical properties of the nanoparticle´s surface and thus the catalytic activity offers an additional benefit of enzyme mimetic bioinorganic NPs over their molecular counterparts.

9055-21

Comparing remineralization of carious lesions in natural and artificial crowns of human teeth

Bert Müller, Lea M. Botta, Hans Deyhle, Iwona Dziadowiec, Peter Thalmann, Basel Univ. Hospital (Switzerland); Shane N. White, Univ. of California, Los Angeles (United States); Lucy Kind, Uwe Pieles, Fachhochschule NordWestschweiz (Switzerland)

The crown of the human teeth exhibits a unique and ordered crystalline structure, which is usually stable for decades and cannot be reproduced by man-made materials of the same quality yet. Attacks of caries bacteria, however, often dissolve the minerals and lead to carious lesions. Today, the dentists remove the affected tissue including some region of healthy crown and subsequently fill the cavity e.g. by an isotropic polymer. Small lesions in the enamel, termed white spots, are often untreated hoping that the attack can be stopped by the improved oral hygiene or remineralized in natural way. In most cases, however, the lesion grows and finally has to be treated.

9055-22

Biomimetic-inspired joining of composite with metal structures: a survey of natural joints and application to single lap joints

Evangelos Ioannis Avgoulas, Michael P. F. Sutcliffe, Univ. of Cambridge (United Kingdom)

Joining composites with metal parts leads, inevitably, to high stress concentrations because of the material property mismatch. Since joining composite to metal is required in many high performance structures, there is a need to develop a new multifunctional approach to meet this challenge. This paper uses the biomimetics approach to help develop solutions to this problem. Nature has found many ingenious ways of joining dissimilar materials and making robust attachments, alleviating potential stress concentrations. A literature survey of natural joint systems has been carried out, identifying and analysing different natural joint methods from a mechanical perspective. A taxonomy table was developed based on the different methods/functions that nature successfully uses to attach dissimilar tissues (materials). This table is used to understand common themes or approaches used in nature for different joint configurations and functionalities.

One of the key characteristics that nature uses to joint dissimilar materials is a transitional zone of stiffness in the insertion site. Several biomimetic-inspired metal-to-composite, adhesively bonded, Single Lap Joints (SLJs) were numerically investigated using a finite element analysis. The proposed solutions offer a transitional zone of stiffness of one or both joint parts to reduce the material stiffness mismatch at the joint. An optimisation procedure was used to identify the variation in material stiffness which minimises potential failure of the joint. It was found that the proposed biomimetic SLJs not only reduce the peak stresses at both ends of the joint, but also reduce the asymmetry of the stress distribution along the adhesive area.

9055-23

Bio inspired smart multifunctional magnet-polymer (MagPol) composites

Anansa S. Ahmed, Raju V. Ramanujan, Nanyang Technological Univ. (Singapore)

There is intense research in the development of innovative materials, structures and systems with life like attributes. Such bio inspired systems can interact and respond to environmental cues. The most promising research directions, especially in soft materials, include damage sensing, healing and actuation. We report our results on magnet polymer composites (MagPol) capable of damage sensing, healing and actuation. These composites are composed of magnetic nanoparticle fillers in a commercially available thermoplastic matrix. The advantages of Magpol based systems include remote, contactless magnetic healing and actuation, self-sensing as well as quick response. Applications include morphing aircraft wings and wind turbine blades, biomedical implants and haptic devices, deployable space structures, MEMS devices and structural health monitoring systems. Mn-Zn ferrite fillers with a range of Curie temperatures (Tc) relevant to the processing window of the thermoplastic Poly (ethylene-co-vinyl acetate) (EVA) matrix, were synthesized. MagPol composites consisting of the magnetic ferrite filler particles in an EVA matrix were prepared. Damage is detected via visible color changes. The color change for various damage levels and loadings was quantified. Effective healing of the damaged region was enabled by subjecting MagPol to an external alternating magnetic field. This magnetic field generated heat in the MagPol, which facilitated chain mobility and healing via reptation. Experimental data for a range of variables, e.g., filler concentration and time will be compared to modeling results. Static and dynamic actuation was also achieved by subjecting MagPol to an external magnetic field. Thus, we have developed a low cost trifunctional magnet-polymer composite capable of sensing, self healing and actuation.

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9055-24

Intelligent agents: adaptation of autonomous bimodal microsystems

Theodore B. Terry, Patrice Smith, Walden Univ. (United States)

Autonomous bimodal microsystems exhibiting survivability behaviors and characteristics are able to adapt dynamically in any given environment. Equipped with a background blending exoskeleton it will have the capability to stealthily detect and observe a self-chosen viewing area while exercising some measurable form of self-preservation by either flying or crawling away from a potential adversary. The robotic agent in this capacity activates a walk-fly algorithm, which uses a built in multi-sensor processing and navigation subsystem or algorithm for visual guidance and best walk-fly path trajectory to evade capture or annihilation. The research detailed in this paper describes the theoretical walk-fly algorithm, which broadens the scope of spatial and temporal learning, locomotion, and navigational performances based on optical flow signals necessary for flight dynamics and walking stabilities. By observing a fly's travel and avoidance behaviors; and, understanding the reverse bioengineering research efforts of others, we were able to conceptualize an algorithm, which works in conjunction with decision-

making functions, sensory processing, and sensorimotor integration. Our findings suggest that this highly complex decentralized algorithm promotes inflight or terrain travel mobile stability which is highly suitable for non-aggressive micro platforms supporting search and rescue (SAR), and chemical and explosive detection (CED) purposes; a necessity in turbulent, non-violent structured or unstructured environments.

9055-26

Influence of bending mode shape and trailing edge deflection on propulsive performance of flexible heaving fins using digital image correlation

Ashok K. Kancharala, Kevin Dewillie, Michael K. Philen, Virginia Polytechnic Institute and State Univ. (United States)

The propulsive performance of flexible flapping fins greatly depends on the stiffness of the fins along with the oscillating parameters. The bending mode shape and trailing edge deflection of the oscillating fins play a major role in the generation of thrust and efficiency. A theoretical and experimental investigation of deformation pattern of the flexible foils and its dependency on propulsive performance is the main focus of this paper.

Experimental investigation has been carried out on fins of various lengths oscillating at their leading edge and LaVision 2D/3D StrainMaster Digital Image Correlation (DIC) system was used to measure the deformation of the fins. A six axis force transducer was used to measure the forces acting on the fin. It is observed that the thrust varies with the deformation mode shape and the trailing edge deflection. For theoretical studies, a fluid structure interaction model has been developed which couples the 2-D unsteady discrete vortex panel method with the nonlinear Euler-Bernoulli beam theory. The developed computational model will be used to predict the thrust and efficiency and compare with the experimental results. A detailed investigation will be carried out on the influence of deformation pattern on propulsive performance and will be reported.

9055-32

Soft materials-derived and reversible nano-lithography

Jae Hong Park, National Nanofab Ctr. (Korea, Republic of)

One of the two main processes of engineering nanostructures is the top down method, which is a direct engineering method for Si-type materials using photolithography or e-beam lithography. The other method is the bottom-up method, using nano-imprinting. However, these methods are very dependent on the equipment used, and have a high process cost. They are also relatively inefficient methods in terms of processing time and energy. Therefore, some researchers have studied the replication of nano-scale patterns via the soft lithographic concept, which is more efficient and requires a lower processing cost. In this study, accurate nanostructures with various aspect ratios are created on several types of materials. A silicon (Si) nanomold is preserved using the method described, and target nanostructures are replicated reversibly and unlimitedly to or from various hard and soft materials. The optimum method of transferring nanostructures on polymeric materials to metallic materials using electroplating technology was also described. Optimal replication and demolding processes for nanostructures with high aspect ratios, which proved the most difficult, were suggested by controlling the surface energy between the functional materials. Relevant numerical studies and analysis were also performed. Our results showed that it was possible to realize accurate nanostructures with high depth aspect ratios of up to 1:18 on lines with widths from 300–400 nm.

In addition, we were able to expand the applicability of the nano structured mold by adopting various backing materials, including a rounded substrate. The application scope was extended further by transferring the nanostructures between different species of materials, including metallic materials as well as an identical species of material. In particular, the methodology suggested in this research provides the great possibility of creating nanostructures composed of various materials, such as soft polymer, hard polymer, and metal, as well as Si. Such nanostructures are required for a vast range of optical and display devices, photonic components, physical devices, energy devices including electrodes of secondary batteries, fuel cells, solar cells, and energy harvesters, biological devices including biochips, biomimetic or biosimilar structured devices, and mechanical devices including micro- or nano-scale sensors and actuators.

9055-33

Analysis of water droplets on the wettability-patterned biomimetic surface

Yuji Hirai, Chitose Institute of Science and Technology (Japan); Hiroyuki Mayama, Asahikawa Medical Univ. (Japan); Yasutaka Matsuo, Hokkaido Univ. (Japan); Masatsugu Shimomura, Tohoku Univ. (Japan)

In nature, there are many functional water-controlling surfaces, such as a water harvest surface of a beetle's back, which is patterned by hydrophobic bumpy surfaces and superhydrophilic surfaces. We have reported that self-organized honeycomb-patterned porous polymer films can be prepared by casting a solution of a hydrophobic polymer and an amphiphilic polymer on a solid substrate by using condensed water droplet arrays as templates. By using honeycomb-patterned films as a mask of a reactive ion etching, superhydrophobic silicon nanospike-array structures can be obtained. Furthermore, surface wettability of this superhydrophobic silicon nanospike-array structures can be selectively modified to superhydrophilic by UV-O3 treatment. In this report, we describe analysis of water droplets behavior on the superhydrophobic-superhydrophilic patterned surfaces. Water droplets on V-shaped superhydrophilic areas surrounded by superhydrophobic areas were immediately spread toward to upper pert of the V-shaped superhydrophilic areas, even if substrates were tilted. By using water contact angle (WCA) analyzer, WCAs and spreading distances were continuously measured. As results, WCAs were decreased with increasing spreading distances, and finally WCAs became c.a. 25 degree. Spreading distances were decreased with increasing tilted angle, and increased with increasing water droplet volume. Interfacial energies of superhydrophobic areas and superhydrophilic areas were calculated by using Kaelble-Uy theory. By using the interfacial energies, final WCAs and spreading distances can be explained. Detail analytical dates will be discussed.

9055-34

Measurement of dynamic characteristics of an artificial wing mimicking an Allomyrina Dichotoma beetle's hind wing using digital image correlation technique

Hoang My Vang, Ngoc-San Ha, Nam Seo Goo, Konkuk Univ. (Korea, Republic of)

Nowadays, the development of flapping-wing micro air vehicles (FW-MAV) has demanded proper design for operation in extreme environmental conditions and biologically inspired wings that can produce enough lift force to keep the vehicles in the air. The structural analysis of an artificial wing is carried out in the design of an FW-MAV. Therefore, this study presents an effective method to measure the full modal parameters of an artificial wing mimicking beetle's hind wing using digital image correlation (DIC) technique. In our measurement, the artificial wing will be mounted on a shaker, which vibrates with a white noise signal. The full-field result as well as the displacement of a single point on the wing over time will be obtained from ARAMIS® software, based on DIC technique. From the temporal displacement of single point signal in time domain, we do fast Fourier transform analysis for this signal and change to the frequency domain in terms of frequency response function (FRF). Thereafter, the natural frequencies and damping factors will be determined from FRF. Finally, the mode shapes will be measured from DIC for the pre-measured natural frequency.

9055-35

Electromagnetic response of the protective pellicle of different unicellular microalgae

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Euglenoids are unicellular aquatic organisms. These microalgae show a typical surface structure that distinguishes them from the other protists. Most cells are naked and bounded by a plasma membrane surrounded by a pellicle formed by overlapping bands.

It is well known that all terrestrial and aquatic organisms are exposed to UV-A and UV-B radiation. This radiation is potentially harmful to life and since it can penetrate up to 12 meters in the water, it can reduce survival, growth and production of phytoplankton. However, the organisms have developed numerous protection mechanisms intended to reduce such damage, such as the production of pigments and other repair mechanisms. However, the possible protection that could provide the first barriers before entering into the cell has not being explored yet.

We investigate, from an electromagnetic point of view, the role played by the pellicle of Euglenoids in the protection of the cell against UV radiation. To do so, we investigate the electromagnetic response of different species that exhibit different behaviors against the UV radiation. We solve the diffraction problem by using the Chandezon Method and obtain the reflectance and absorbance of the pellicle for the UV wavelengths. The results show that the corrugated pellicle could contribute to increase the reflectance and to decrease the absorbance, thus reducing the penetration of the UV radiation within the cell and therefore, minimizing the damage and increasing the survival of these organisms.

9055-37

Biomimetic surfaces of semiconducting metal oxides

Kosuke Orita, Olaf Karthaus, Chitose Institute of Science and Technology (Japan)

Biomimetic preparation of functional surfaces is interesting from several viewpoints: low energy cost during preparation, multiple functionality because of the hierarchic structure, and easy recyclability at the end of the life cycle. We use a wet process to prepare honeycomb structures from a solution of a polymer cats at high humidity. The honeycomb films act as templates for the adsorption of functional metal oxides, such as titanium dioxide, tungsten oxide, sink oxide, and so on. The films show increased photocatalytic activity and wetting properties due to the hierarchic structure of nanocrystalline metal oxide and microscopic pattern

9055-38

Dragonfly hover is primarily mediated by vision

Javaan S. Chahl, Univ. of South Australia (Australia) and Defence Science and Technology Organisation (Australia); Akiko Mizutani, Odonatrix Pty. Ltd. (Australia)

Hovering flight is a capability that we would like to implement in machines. There are aspects of mechanism, sensor and processing to be understood. The sensory means by which hover is achieved could be inertial, visual or a herein null hypothesized unexplained sensor system. In order to obtain reasonable certainty as to the means by which hover is measured, an experiment was performed. Dragonflies of the Australian species Hemianax papuensis were filmed in their natural breeding habitat. In these environments dragonflies hover for extended periods over bodies of water in order to defend oviposition sites.

Wind gusting between 2m/s and 6m/s was present. The position of the Dragonfly while hovering relative to the environment was captured at 50Hz from a tripod mounted video camera. Dragonflies were shown not to maintain a stationary position in wind. Their position fluctuated significantly while returning to the original position. The movement of the dragonfly is correlated with the movement of vertically standing vegetation. Video analysis showed that there was less than 100ms delay between the movement of the standing vegetation and the movement of the dragonfly. This response would be non-causal with wind for an inertial or putative pressure based internal sensory system. It is postulated that with a substrate of moving water, sensitivity to movement on the visual horizon for controlling hover is a robust strategy. Questions are raised by this result about the use of comparatively weak loom stimuli for a high gain control system.

9055-39

Optimization of the leading edge segment of a corrugated wing

Javaan S. Chahl, Univ. of South Australia (Australia) and Defence Science and Technology Organisation (Australia); Manas S. Khurana, RMIT Univ. (Australia)

Insect wings consist of flat plates of membrane stiffened by spars. The effect of this structure is that the wings appear as corrugated surfaces when considered on chordwise sections. The consensus in the literature is that there are aerodynamic and/or aerostructural benefits to such structures at low Reynolds numbers. We know that aerodynamically efficient insects such as dragonfly engage in fixed wing flight modes for extended periods. We have developed a computational framework for optimizing a corrugated wing to a specific Reynolds number across a sweep of angle of attack. Our technique uses the length and angle of each connected segment of the corrugation as genes in a genetic algorithm to optimize the aerodynamic performance of the wing. Meshes for the solution of the computational fluid dynamics were produced algorithmically based on the current shape of the corrugated wing. The system is executed on a supercomputer running the Fluent computational dynamics package.

In these early results the angle of the first corrugation of the wing, a single "gene", was varied to find the highest aerodynamic efficiency. The aerodynamic efficiency of the wing was increased by over 15%, from a lift to drag ratio of 6 to over 7 at a Reynolds number of 34000. The search algorithm was executed at this Reynolds number due to the availability of wind-tunnel data. We postulate that significant improvements will be found as more genes are modified at lower Reynolds numbers postulated by others to be appropriate for corrugated wings.

9055-40

A new nonlinear model for studying morphing forces and moments acting on an articulated micro air vehicle

Adetunji Oduyela, The Univ. of Alabama in Huntsville (United States)

Wing articulation in birds have been a very efficient method of adjusting their body shape to take advantage of favorable wind conditions or reduce loads on certain body segments under prevailing flying conditions. While there has been recent interest in the design and use of articulated winged air vehicles to mimic nature, success has been limited to the smaller scale of micro air vehicles due to their smaller structural frames and weight. A major limitation of the articulated winged concept to much larger flying machines is in the larger values of the joint loads they experience while changing their shapes, such stress and strains are known to demand much stiffer and heavier structural and joint components. Lower joint load values have allowed the development and use of articulated winged micro air vehicles for various activities, but their use has been limited to steady wind conditions where the passive changes in shapes are less abrupt or where the controlled shape changes are known well in advance. To allow the increase in the operational flight envelope of articulated micro air vehicles beyond that allowed using present mathematical models requires the prediction and monitoring of the changing joint loads acting on the vehicle. The mathematical model presented in this paper reveals the unknown instantaneous forces and moments acting on an articulated winged micro air vehicle during flight, allowing the development of smart controllers that take into account the joint loads and structural limitations of any particular air vehicle configuration. The proposed model for the articulated winged micro air vehicle is validated against data obtained from flight tests conducted in the UAHuntsville's Autonomous Tracking and Optical Measurements laboratory, and later used to study the changes in the joint loads for vehicle configurations with varying joint locations and joint stiffness parameters, as well as for different maneuvers and varying wind conditions like a head-on or crosswind gusts.

9055-42

Development of multimodal bubble contrast agent using SiO2 as templates for biomedical application

Hsiu-Ying Huang, Walter H. Chang, Tzu-Ying Hou, Chung Yuan Christian Univ. (Taiwan)

In this study, we introduced contrast agents synthesized by using SiO2 particles as a template. The SiO2 were coated polymer and metal nanoparticles to form core shell laminate. To create an ultrasound-sensitive particle, a SiO2 core was hydrofluoric acid etched to produce hollow capsules laminated. And the bubbles are stable and can enhance the contrast under continually ultrasound exposure for 30 minutes. And the MTT test showed better biocompatibility between cell coculture with bubbles. The ultrasound contrast agents were characterized by dynamic light scattering (DLS), transmission electron microscopy (TEM), scanning electron microscope (SEM), and diagnostic doppler ultrasound system. Based on the current reports and previous breakthrough finding from other groups, we believe the ultrasound contrast agent will offer many great potential application to medical ultrasound research.

9055-27

Micro-pixelation and color mixing in biological photonic structures *(Invited Paper)*

Michael H. Bartl, Ramneet K. Nagi, The Univ. of Utah (United States)

The world of insects, birds, and marine animals displays myriad hues of colors and optical effects in form of brilliantly colored wings, exoskeleton, and skin. A large number of these colors and effects are not the result of pigments, but arise from a delicate interplay of light and periodically organized structures with feature sizes of a few hundreds of nanometers. Excellent examples of such structural colors can be found in colored scales of beetles. We have recently found that the families of weevils and longhorn beetles possess particularly interesting photonic architectures with cubic lattices. In this talk, we will present our high-resolution structure analysis technique based on focused ion beam milling, electron microscopy and photonic band structure modeling. Using this technique we were able to obtain high-resolution three-dimensional reconstructions of photonic structures from blue, green and red-colored weevils. Surprisingly, we discovered that in most weevils the color-producing photonic crystal structures are all based on diamond and gyroid lattices—also termed the champions of photonic crystal lattices. Moreover, by three-dimensionally reconstructing entire scales we found each scale to be an array of differently oriented single-crystalline domains. These single-crystalline domains are organized such that only selected crystal faces are oriented parallel to the scale surface, visible to an observer. We found this pixel-like arrangement to be the reason for the uniform, angle-independent coloration typical of weevils. We will discuss how similar color-mixing micro-pixelation strategies could be used to control light reflection and transmission in advanced coating technologies.

9055-28

Waveguiding in nature *(Invited Paper)*

Vasudevan Lakshminarayanan, Univ. of Waterloo (Canada)

Waveguiding seems to be ubiquitous in nature. These include for example, vertebrate photoreceptors (rods and cones of the retina), cochlear hair cells of the human ear, human hair (cilia), fiber optic plant tissues, and glass sponges (Euplectella). Many of these systems evolved millions of years ago These systems can be analyzed using standard techniques of waveguide/fiber optics assuming cylindrical geometry. In this talk I will present examples of these waveguiding systems. These studies give us greater insight into low temperature, biologically inspired processes and could have implications for design and construction of better fiber optic materials and networks.

9055-29

Analysis of light-coupling efficiency of a solar cell with bioinspired pit texturing

Francesco Chiadini, Univ. degli Studi di Salerno (Italy); Vincenzo Fiumara, Univ. degli Studi della Basilicata (Italy); Antonio Scaglione, Univ. degli Studi di Salerno (Italy); Akhlesh Lakhtakia, The Pennsylvania State Univ. (United States)

Efforts are being made continually to improve the efficiency of silicon solar cells. The strategies employed include the use of anti-reflective layers, texturing of the front silicon surface, mechanical solar tracking, and the use of concentrators. Inspired by the apposition compound eyes of some dipterans, earlier we demonstrated theoretically [1] that the exposed surfaces of silicon solar cells could be textured as arrays of bioinspired compound lenses in order to improve performance. In particular, the exposed face was textured as an array of parallel prisms whose cross-section is a circular arc (defined as 0th-stage texture) which is decorated further by N1 smaller circular arcs (1st-stage texture). We call this texture the bioinspired hillock texture. Now, we have analyzed another bioinspired texture that is the negative of the hillock one. The prisms are replaced by grooves in the bioinspired pit texture. Within a spatial regime for which geometrical optics is valid [2] and considering the complex-valued nature of the refractive index of silicon, generalized reflection and refraction laws as well as generalized Fresnel coefficients [3] were used to evaluate the light-coupling efficiency of the solar cell. A multifrequency analysis allowed us to determine the values of morphological parameters optimizing the performance of the bioinspired pit texture. Numerical simulations taking into account the broadband nature of solar radiation and its amplitude at the sea level (AM1.5G spectrum) demonstrated that the light-coupling efficiency can be enhanced by as much as 24% with respect to that of a silicon cell with a planar exposed face, and that the bioinspired pit texture somewhat outperforms its hillock counterpart.

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9055-30

Polymer based flapping-wing robotic insect: progress in design, fabrication, and characterization *(Invited Paper)*

Alexandre Bontemps, Thomas Vanneste, Univ. des Sciences et Technologies de Lille (France); Caroline Soyer, Sebastien Grondel, Eric Cattan, Univ. des Sciences et Technologies de Lille (France) and Univ. de Valenciennes et du Hainaut-Cambrésis (France)

In the last decade researchers pursued the development of tiny flying robots inspired by natural flyers. Our main objective is to devise a flying robot mimicking insect in terms of kinematics and scale using MEMS technologies. For this purpose, an original design has been developed around resonant thorax and wings by the way of an indirect actuation and a concise transmission whereas the all-polymer prototypes are obtained using a micromachining SU-8 photoresist process. This paper reports our recent progress on the design of a flapping-wing robotic insect as well as on the characterization of its performance. Prototypes with a wingspan of 3 cm and a mass of 22 mg are achieved. Due to the introduction of an innovative compliant link, large and symmetrical bending angles of 70° are achieved at a flapping frequency of 30Hz along with passive wing torsion while minimizing its energy expenditure. Furthermore, it leads to a mean lift force representing up to 75 % of the prototype weight as measured by an in-house force sensor. Different improvements are currently underway so as to increase the power-to-weight ratio of the prototype and to obtain an airborne prototype. Actuator is being improved further in order to minimize its mass while increasing its force production towards a greater bending angle. The transmission is being modified so as to enhance its amplification and favor the wing torsion. The wing architecture is also tuned aiming at increasing the flapping frequency and the passive torsion necessary for the lift generation.

9055-31

A three-dimensional iterative panel method and boundary layer model for bioinspired multi-body wings

Christopher J. Blower, Adam M. Wickenheiser, The George Washington Univ. (United States)

The increased use of Unmanned Aerial Vehicles (UAVs) has created a continuous demand for improved flight capabilities and range. During the last decade, engineers have turned to bio-inspiration for new and innovative flow control methods for gust alleviation, maneuverability, and stability improvement using morphing aircraft wings. The bio-inspired wing design considered in this study mimics the flow manipulation techniques performed by birds to extend the operating envelope of UAVs through the installation of an array of feather-like panels across the airfoil's upper and lower surfaces while replacing the trailing edge flap. Each flap has the ability to deflect into both the airfoil and the inbound airflow using hinge points with a single degree-of-freedom, situated at the 20%, 40%, 60% and 80% of the chord. The installation of the surface flaps offers configurations that enable advantageous maneuvers, while alleviating gust disturbances. Due to the number of possible permutations available for the flap configurations, an iterative constant-strength doublet/source panel method has been developed with an integrated boundary layer model to calculate the pressure distribution and viscous drag over the wing's surface. As a result, the lift, drag and moment coefficients for each airfoil configuration can be calculated. This model is extended into three-dimensions while implementing a two-dimensional boundary layer that enables the viscous drag characteristics to be modeled piece-wise across the wingspan for all flap configurations, allowing the wing's maneuverability and stability to be modeled. The flight coefficients of this numerical method are validated using experimental data from a low speed suction wind tunnel operating at a Reynolds Number 300,000. This method enables assessment of a morphing wing profile to be performed accurately and efficiently in comparison to Computational Fluid Dynamics methods and experimental results as discussed herein.

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9056-1

Soft robotics: a review and progress towards faster and higher torque actuators *(Keynote Presentation)*

Robert Shepherd, Cornell Univ. (United States)

Last year, nearly 160,000 industrial robots were shipped worldwide—into a total market valued at ~$26 Bn (including hardware, software, and peripherals).[1] Service robots for professional (e.g., defense, medical, agriculture) and personal (e.g., household, handicap assistance, toys, and education) use accounted for ~16,000 units, $3.4 Bn and ~3,000,000 units, $1.2 Bn respectively.[1] The vast majority of these robotic systems use fully actuated, rigid components that take little advantage of passive dynamics. Soft robotics is a field that is taking advantage of compliant actuators and passive dynamics to achieve several goals: reduced design, manufacturing and control complexity, improved energy efficiency, more sophisticated motions, and safe human-machine interactions to name a few. The potential for societal impact is immense. In some instances, soft actuators have achieved commercial success; however, large scale adoption will require improved methods of controlling non-linear systems, greater reliability in their function, and increased utility from faster and more forceful actuation. In my talk, I will describe efforts from my work in the Whitesides group at Harvard to prove sophisticated motions in these machines using simple controls, as well capabilities unique to soft machines. I will also describe the potential for combinations of different classes of soft actuators (e.g., electrically and pneumatically actuated systems) to improve the utility of soft robots. 1. World Robotics - Industrial Robots 2013, 2013, International Federation of Robotics.

9056-2

Artificial muscles harvesting sensational power *(Invited Paper)*

Thomas G. McKay, The Univ. of Auckland (New Zealand); Todd A. Gisby, StretchSense (New Zealand); Iain A. Anderson, The Univ. of Auckland (New Zealand)

Dielectric elastomer Generator(s) (DEG) are highly suited to harvesting from environmental sources because they are light weight, low cost, and can be coupled directly to rectilinear motions and harvest energy efficiently over a wide frequency range. Because of these benefits, a simple and therefore low cost system could be enabled using DEG.

Electrical energy is produced on relaxation of a stretched, charged DEG: like-charges are compressed together and opposite-charges are pushed apart, resulting in an increased voltage. The manner in which the DEG charge state is controlled greatly influences the amount of energy that is produced. For instance, the highest energy density ever demonstrated for DEG is 550 mJ/g, whereas the theoretical energy density of DEG has been reported as high as 1700 mJ/g if driven close to their failure limits.

The discrepancy between realised and theoretical energy production highlights that large performance gains can be achieved through smarter charge control that drives the generator close to its failure limits. To do so safely, we need to be able to monitor the real-time electromechanical state of the DEG. This paper will discuss the potential of self-sensing for providing feedback on the generator's electromechanical state. Then we will discuss our capacitive self-sensing method which we have demonstrated to track the displacement of a Danfoss Polypower generator as it was cyclically stretched uniaxially and harvested energy.

9056-3a

Durability of dielectric elastomer actuators made with ionic conductors

Philipp Rothemund, Christoph Keplinger, Jeong-Yun Sun, Harvard Univ. (United States); Qin Li, Mejdi Kammoun, Univ. of Houston (United States); David Bwambok, Harvard Univ. (United States); Haleh Ardebili, Univ. of Houston (United States); George M. Whitesides, Zhigang Suo, Harvard Univ. (United States)

Dielectric elastomer actuators are of soft electrostatic actuators, which consist of a soft dielectric elastomer membrane, sandwiched between two layers of compliant, electrically conductive materials. When a voltage is applied between the conductive layers, electrostatic forces cause the elastomer membrane to decrease in thickness and increase in area. Electronically conducting materials are almost exclusively used for the conducting layers. Recently an approach was presented to make dielectric elastomers transparent by using ionic conductors for the conductive layers, and that allows operation at high frequencies and voltages whereas avoiding electrochemical reaction. Replacing electrons with ions as charge carriers in the conductive layers involves new physics and can lead to phenomena which influence the durability and reliability of dielectric elastomer actuators. For example the migration of ions into the dielectric layer under the influence of high electric fields can lower the durability of dielectric elastomer actuators and is not yet extensively studied. This report presents an experimental investigation of the durability of dielectric elastomer actuators when different ionic conductors are used using the example of prestretched circular actuators. Tested are actuators with conductive layers made out of non-volatile ionic liquids and a hydrogel, which is swollen with a NaCl solution. The number of actuation cycles before failure for each material is compared with the cyclic lifetime of actuators made with electrodes out of carbon grease. The compatibility of the ionic conductors with the dielectric layer is identified as crucial for the durability of the dielectric elastomer actuators.

9056-4a

Effects of electrode surface structure on the mechanoelectrical transduction of IPMC sensors

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This study investigates the effects of electrode surface structure on the mechanoelectrical transduction of IPMC sensors. A physics-based mechanoelectrical transduction model was developed that takes into account the electrode surface profile (shape) by describing the polymer/electrode interface as a Koch fractal structure. Based on the model, the electrode surface effects were experimentally investigated in case of two types of electrodes – Pd-Pt and our newly designed Pt electrodes with nanothorn assemblies. IPMCs with different electrode surface structures were fabricated through electroless plating process by appropriately controlling the synthesis parameters. The changes in the electrode surface morphology and the corresponding effects on the IPMC mechanoelectrical transduction were examined. The experiments indicate that the formation and growth of platinum nanothorn assemblies at the polymer/electrode interface leads to a higher peak mechanoelectrically induced voltage of IPMC. More pronounced

increase in the induced voltage amplitude was observed in case of Pd-Pt electrodes by increasing the content of Pd particles near the membrane surface. However, the overall effect of the electrode surface structure was relatively low compared to the electromechanical transduction, which was in good agreement with theoretical prediction.

9056-5a

Geometry optimization of tubular dielectric elastomer actuators with anisotropic metallic electrodes

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Dielectric elastomer (DE) actuators, manufactured by Danfoss PolyPower A/S, are core free tubular structures formed by winding PolyPower DE laminated sheets. The laminates consist of two DE sheets each with one corrugated surface being coated by silver electrode.

The corrugated surface together with application of metallic electrodes introduces anisotropy in the laminated sheets, i.e. the DE sheets are more compliant along the corrugation pattern. When rolled in a tubular structure, the compliant direction of the sheet is along the symmetry axis of the tube while the stiff direction is along the circumference of the tube. If the DE laminate is winded tightly, adjacent DE layers are not able to slide relative to each other when electrically stimulated. Thus the actuator, seen as a metamaterial, will be significantly stiffer in the direction along the circumference of the tube relative to the direction of the symmetry axis. Due to this anisotropy the performance of the DE actuator is strongly dependent on geometry.

This paper characterizes and optimizes the performance of tubular DE actuators based on their geometrical parameters such as aspect ratio of elliptical cross section, wall thickness, and height. The performance of tubular actuators for different geometries are modeled and simulated in the FEM software COMSOL and compared with experimental results. Optimized geometry shows that the actuators will exhibit better performance while preserving their structural stability.

9056-6a

Impact of electrode preparation on the bending of asymmetric planar electro-active polymer microstructures

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Compliant electrodes of microstructures have been a research topic for many years because of the increasing interest in consumer electronics, robotics, and medical applications. This interest includes electrically activated polymers (EAP), mainly applied in robotics, lens systems, haptics and foreseen in a variety of medical devices. Here, the electrodes consist of metals such as gold, graphite, conductive polymers or certain composites. The common metal electrodes have been magnetron sputtered, thermally evaporated or prepared using ion implantation. In order to compare the functionality of planar metal electrodes in EAP microstructures, we have investigated the electrical and mechanical properties of magnetron sputtered and thermally evaporated electrodes taking advantage of cantilever bending of the asymmetric, rectangular microstructures [F. M. Weiss et al.: Measuring the bending of asymmetric planar EAP structures, Proc. of SPIE 8687 (2013) 86871X]. We demonstrate that the compliance of the sputtered electrodes is 15 % larger than that of thermally evaporated nanometer-thin film on a single silicone film. The related conductance measurements are not only relevant for the temporal response of the EAP structure but also characteristic for the defect level and the fatigue behaviour. Although the 15 % difference in compliance might be regarded as small, it becomes prominent for nanometer-thin multi-layered EAP structures desired for low-voltage applications in the medical field.

9056-7a

Design and characterization of a stacked dielectric elastomer actuator based on SWNT electrode and IPN composite films

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Dielectric elastomer based on 3M VHB tapes have shown excellent mechanical strains and energy density, such performance has entitled the acrylic film a promising candidate for artificial muscle. However, defects inherently from the film present in the actuator such as short lifetime and weak driving force. In this paper, single-walled carbon nanotube (SWNT) and acrylic film with interpenetrating polymer networks (IPN) were applied to dielectric elastomer actuator (DEA) with combination. The SWNT electrode exhibits fault-tolerance characteristic through the local degradation of carbon nanotubes during dielectric breakdown. The IPN composite film can eliminate the stress of the prestrained film that the film no longer easily breaking. A stacked DEA made of SWNT and IPN was constructed to increase the DEA's driving force and lifetime. To insure the electrode thickness and uniformity, a spraying machine was designed, that will also be of great benefits to analyze the quantitative influence of corresponding parameters. A new preloaded mechanism was also designed due to the decrease of stickiness between each layer of the stacked actuator. As a result, longer lifetime and larger driving force was gained with the combination of SWNT electrode and IPN. The quantitative influence of liquid additives mass and the SWNT thickness on the DEA's performances were also analyzed.

9056-8b

ViviTouch HD Feel enables advanced and multi-dimensional communication through touch

Dirk Schapeler, ViviTouch | A Bayer Brand (United States)

Beyond visual cues, what types of multisensory feedback is being used by devices to communicate with the user? Furthermore, when the sense of touch is used, why is there an absence of a haptic vocabulary to truly help differentiate between various functions? We will explore various ways that have been used to communicate between devices and users. We will also attempt to understand why realistic and differentiated feel beyond a simple one dimensional buzz against your skin is lacking. Finally we will explain how ViviTouch® HD Feel we can truly develop a haptics language and can change how wearable devices communicate in a multi-dimensional way with users.

9056-9b

Dielectric elastomer driven adaptive lens arrays for fly-eye optical detectors

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Fly-eye type optical detectors allow for 180-degree viewing through the placement of multiple lenslets around a hemispherical superstructure, reducing image distortion and increasing the field of view relative to a single, monolithic lens. This biological design serves as inspiration for the fabrication of a curved lens array where each individual lens can tune its focal length electrically. Using adaptive lenses increases the versatility of the array, affording higher resolution and improved object detection at multiple focal lengths. Recent advances in liquid adaptive lenses have shown that high-speed focal change can be achieved using transparent dielectric elastomer actuators, consequently enabling the assembly of a lens array in a self-contained, compact package. Details of device fabrication, electromechanical performance, and optical characterization will be presented. Potential applications of such a device include robot vision, imaging, and surveillance.

9056-10b

Biodegradable and edible gelatine actuators for use as artificial muscles

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The expense and use of non-recyclable materials often requires the retrieval and recovery of exploratory robots. Therefore, conventional materials such as plastics and metals in robotics can be limiting. For applications such as environmental monitoring, a fully biodegradable or edible robot may provide the optimum solution. Materials that provide power and actuation as well as biodegradability provide a unique coupling of technological advances for future robotic systems.

To highlight the potential of novel biodegradable and edible materials as artificial muscles, the actuation of a biodegradable hydrogel was measured. The fabricated gelatine based polymer gel was inexpensive, easy to handle, biodegradable and edible. The electro-mechanical performance was assessed using two contactless, parallel stainless steel electrodes immersed in 0.1M NaOH solution and fixed 40 mm apart with the strip actuator pinned directly between the electrodes. The actuation displacement in response to a bias voltage was measured over hydration/ de-hydration cycles. Long term (11 days) and short term (1 hour) investigations demonstrated the bending behaviour of the swollen material in response to an electric field. Actuation voltage was low (<10 V) resulting in a slow actuation response with large displacement angles >55 degrees. The stability of the immersed material decreased within the first hour due to swelling, however, was recovered on de-hydrating between actuations. The controlled degradation of biodegradable and edible artificial muscles could help to drive the development of environmentally friendly robotics.

9056-11b

Soft silicone based interpenetrating networks as materials for actuators

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Silicone elastomers have been heavily investigated as materials for dielectric electroactive polymers due to their many favorable properties. The major shortcoming of silicones compared to the other elastomer candidates is the low dielectric permittivity. The commercial silicone elastomers are all reinforced since the tear strength of the pure polymer network is too low. Therefore the addition of permittivity enhancing fillers to the already filled elastomer may lead to a significant increase in the Young's modulus. Sometimes the increase in the Young's modulus is even higher than the increase in the permittivity and thereby leads to an overall reduction of the actuation.

Electroactive interpenetrating networks based on both acrylic and silicone elastomers have been thoroughly investigated by the group of Q. Pei, UCLA, with the main focus on preparing pre-strained films for improved actuation properties.

In this work a new approach based on interpenetrating silicone networks with orthogonal chemistries has been investigated with focus on developing soft and flexible elastomers with high energy densities and small viscous losses. The orthogonal chemistry could allow for pre-strain but this is not the focus of this work. The interpenetrating networks are made as simple two pot mixtures as for the commercial available silylation based elastomers such as Elastosil RT625 from Wacker Chemie AG. The resulting interpenetrating networks are formulated to be softer than Elastosil RT625 to increase the actuation caused when applying a voltage as well as they possess significantly higher permittivity than the pure silicone elastomers.

9056-12b

A novel method of fabricating laminated silicone stack actuators with pre-strained dielectric layers

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Stack based dielectric elastomer actuators (DEAs) have shown to be effective at delivering biomimetic contractile strains. However, limitations in the fabrication and construction of the stacks constrain their use beyond the research environment. This paper focuses on a fabrication process to enable a stacked silicone (Dow Corning Silastic 3483) actuator to withstand high tensile forces and contract with a low actuation voltage. Spun silicone layers are bonded together in a pre-strained state using a conductive silicone filler, forming a laminated inter-penetrating network (L-IPN) with repeatable electrode thickness. The resulting structure utilises the stored strain energy of the dielectric elastomer to enable compression of cured electrode material, which enhances conductivity through its compressive action. Furthermore the bonded L-IPN allows increased tensile loads to be achieved, which in previous fabrications has been limited by the vacuum formed conductive grease between alternating plies of dielectric elastomer. The described process is used to fabricate a stack of pre-strained dielectric layers supported by a thin conductive substrate, which possess a tensile strength greater than 50 N/cm2 and operate at <1kV. It is also shown how the method of bonding allows regulation of the electrode to dielectric thickness ratio, hence enabling maximisation of overall effective actuator contraction.

9056-13a

Carbon-based torsional and tensile artificial muscles driven by thermal expansion *(Invited Paper)*

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Materials with large volumetric thermal expansion can provide mechanical work when heated and cooled. However, their application towards artificial muscles has been limited by characteristically low strokes and a difficulty in configuring them as tensile actuators. In order to overcome these obstacles, we employ fiber materials with such a high degree of alignment that they exhibit anisotropic thermal expansion. By inserting twist into these fibers, structural changes are induced which allow them to provide thermally-driven torsional actuation. Most importantly, at sufficient twist densities this twist drives the formation of helical coils. Such coiled structures can provide giant-stroke tensile actuation exceeding the 20% in-vivo contraction of natural muscles. This contraction is highly reversible, with over one million cycles demonstrated, and can occur without the hysteresis that plagues competing shape-memory and piezoelectric muscles. These muscles can also be driven electrothermally by adding conductive coatings such as carbon nanotube sheets, as well as hydrothermally driven using hot and cold water. This advance opens the possibility for textiles that are woven or knitted from thermally-responsive fibers to provide smart textiles and fabrics that change porosity to provide wearer comfort.

9056-14a

Recent progress on graphene-based artificial muscles *(Invited Paper)*

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Graphene, a single layer assembly of carbon atoms densely packed into a benzene ring structure have unique properties thus making it a potential material for applications in next-generation electronic devices, reinforced composites for electrical and thermal conduction, transparent electrodes for displays, solar cells, chemical and biological sensors, nano-composites and others. Recently, some contribution to graphene-based artificial muscles has been made to overcome some drawbacks of conventional artificial muscles. First, we report microwave-based syntheses for graphene and graphene hybrid nanomaterials that can be used for high-performance artificial muscles. A novel defect engineering to synthesize graphene flakes, metal nanoparticle-decorated graphene, graphene-based 3D carbon nanostructures by using some chemicals and microwave radiation was developed recently. Microwave radiation as external energy source was used to produce strong expansion of the graphite worm along the thickness direction and to induce high temperature environment that is a prerequisite for activating chemical reactions and for constructing hybrid nanostructures. The basic properties of those carbon nanostructures are carefully investigated in view of electro-chemo-mechanical properties. Finally, we will demonstrate several graphene-based artificial muscles including helical shape memory polymer stent, highly durable IPGC actuator, GO-SPI composite actuators and transparent ionic polymer actuators.

9056-15a

The viscoelastic effect in bending bucky-gel actuators

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Electromechanically active polymers (EAP) are considered a good candidate for actuators for a variety of reasons such as they are soft, easy to miniaturize and operate without audible noise. The main structural component in EAPs is, as the name states, some type of deformable polymer. As polymers are known to exhibit very distinct mechanical response, the nature of polymer materials should never be neglected when characterizing and modeling the performance of EAP actuators. Bucky-gel actuators are a subtype of EAPs where ion-containing polymer membrane acts as a dielectric separator between two electrodes of carbon nanotubes and ionic liquid. In many occasions, the electrodes also contain polymer for the purpose of binding it together. Therefore, mechanically speaking, bucky-gel actuators are composite structures with layers of different mechanical nature. The viscoelastic response and the shape change property are perhaps the most characteristic effects of polymers. These effects are known to have high dependence on factors such as the type of polymer, the concentration of additives and the structural ratio of different layers. At the same time, most reports on optimizing EAP actuators describe the alteration of electromechanical performance dependent on the same factors. This paper investigates the two principal effects (viscoelasticity and shape change property) of bucky-gel actuators and how they affect the actuation performance of bending bucky-gel actuators.

9056-16a

Electroactive nanostructured polymers actuators

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Electroactive nanostructured polymer actuators have garnered attention as promising candidates for next generation compact actuators, sensors, artificial muscles and micro robotics, owing to their attractive properties such as large electromechanical strain, fast response, high power to mass ratio, facile proccessibility, and affordability. The present work demonstrates that electroactive nanostructured polymers like a block copolymer can provide an unexpected large actuation performance due to their structural feature such as a high density of microphase-separated nanodomains and large domain size. In the dielectric elastomer actuation, a large density of dielectric mismatched nanodomains of the nanostructured polymers results in an unexpected ultralarge electrostriction coefficient, enabling a large electromechanical strain response at a low electric field. This strong electrostrictive effect is attributed to the development of an inhomogeneous electric field across the film thickness due to the high density of interfaces between dielectric mismatched periodic nanoscale domains. In the ionic polymer metal composite (IPMC) actuation, the microphase-separated big-size ionic domains of the nanostructured polymers on the several tens nanometer scale can provide unexpectedly larger ion conductivity, larger air-working bending displacement and faster bending rate without conventional IPMC drawbacks, including back relaxation and a sacrifice of mechanical strength.

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9056-17b

A tapped-inductor buck-boost converter for a multi-DEAP generator system

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Research on the competency of Dielectric ElectroActive Polymers (DEAPs) in energy harvesting applications has been constantly gaining momentum during the past few years, due to their profound advantages against competing electromagnetic and field-activated technologies. However, the low-frequency, high-amplitude pulsating voltage signal across the DEAP generator electrodes during normal operation, in conjunction with the lack of commercially-available, high-efficient, high-voltage, low-power semiconductor devices, has boosted the scientific interest around active power electronic converters that may drive the DEAP generator closer to its rated E-field value than the rest low-efficient passive approaches. In this paper, a high-efficient (>90 %), tapped-inductor buck-boost converter, based on a string of three serialized MOSFETs, is used to harvest energy from a DEAP generator installed on a multi-generator test rig, where all four generators are installed out-of-phase in order for their retracting forces to cancel out. The system energy harvesting efficiency, as well as the DEAP energy conversion efficiency, is documented based on numerous experimental results.

9056-18b

Buckling effects on actuation and energy harvesting in IPMCs

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In the last decade, ionomeric polymer-metal composites are emerged as viable intelligent materials working both as bending actuators and energy harvesting systems. Recently, the feasibility of actuation from mechanical buckling has been investigating [1,2]. In the present research, we present relevant numerical and experimental progress towards the possible electromechanical transduction from buckled configurations when different patterned electrodes are considered, and the energy harvesting in presence of buckling-induced deformation modes.

As it is well known, when mechanical buckling is considered, it is fundamental to account for both the total stress and total energy within the system. The physics-based IPMC models separately developed by the Authors ([3,4]) allow for a rational representation of the total free energy involved in the IPMC dynamics, and for the important contribution of the Maxwell stress with respect to the total stress, particularly relevant when high voltages are involved. Based on these models, we investigate the possibility of actuation and energy harvesting from IPMCs through mechanical buckling. The focus of this research is theoretical and numerical, while some initial experimental model verifications are performed.

In particular, with reference to one-dimensional IPMC strips and considering the large influence of electrodes's bending stiffness on the IPMC behaviour [4], (1) we conjecture that appropriate patterned electrodes might enable specific buckling modes, (2) we investigate the role of the metal electrodes on the mechanical buckling, and (3) we discuss the effectiveness of energy harvesting when smooth and buckled IPMC dynamics is involved.

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9056-19c

Characterization of dielectric electroactive polymer transducers

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Introduction:

Electrodynamic transducers have dominated the market of sound reproduction for a century. The Dielectric ElectroActive Polymers (DEAP) is proposed as a very interesting alternative to these inefficient and bulky transducers. In order to design not only the loudspeaker itself, but also the amplifier driving the DEAP transducer, the small-signal model of the DEAP transducer must be known.

Theory:

The DEAP transducer is nonlinear, and the pressure increases with the square of the applied voltage. A linearized small-signal model of the DEAP transducer is derived using the model of the condenser transducer and the mechanical impedance analogy.

Analysis:

The small-signal model is used to analyze the electrical impedance of the DEAP transducer. It is shown, that the electrical capacitance dominates the impedance. However, at high biasing voltages the coupling between the electrical and mechanical domain improves enough for the mechanical resonances to appear in the impedance plot.

Experimental results:

The AP300 impedance/gain-phase analyzer is used to perform the measurements. A RC-circuit with a large capacitor-bank ensures that the bias voltage can be coupled to the DEAP transducer without the output impedance of the high voltage power supply affecting the measurements. The measurements are performed on a 100 nF DEAP transducer with a breakdown voltage of 2.5 kV. The change in electrical capacitance is shown as function of the biasing voltage. Further more the measured impedance as function of frequency for each biasing point is presented. The measured small-signal impedance is related to the proposed model with an accuracy of ± 5 %.

9056-20c

An instrument to obtain the correct biaxial hyperelastic parameters of silicones for accurate DEA modelling

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Recent progress on DEA modelling has explained several particular behaviours of DEAs, such as EMI suppression by prestretching, giant deformations etc. The analytical models rely on the use of strain energy functions modelling the mechanical behaviour of the elastomeric membranes. Among the different hyperelastic models, the Gent model is often used, because it predicts the stiffening caused by the finite length of the polymer chains. However, we show that the Gent model is not suitable for all elastomers, such as silicones, which are also widely used within the EAP community. Furthermore, the parameters of hyperelastic models are often obtained through fitting of uniaxial pull tests and are subsequently used to predict the equi-biaxial behaviour of the material, which is an additional source of error.

We have built a bubble tester in order to extract the stress vs. stretch curve for the equi-biaxial loading case. This allows using the analytical models with a lookup table instead of a material model, thus predicting more precisely the strain as a function of voltage of DEAs. Our bubble tester consists in a regulated pressure source used to inflate a thin silicone membrane; a camera is used to measure the stretch at the apex of the bubble, where the stress state is equi-biaxial. Our results show that uniaxial characterization alone is not sufficient to predict the behaviour

of DEAs and that equi-biaxial testing is also required. Furthermore, the common hyperelastic models cannot accurately describe the behaviour of some silicones and should be used with caution.

9056-21c

Novel dielectric elastomer structures with electromechanical instability

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Dielectric elastomer (DE) actuators can convert electrical energy to mechanical energy. However, actuating DE membranes requires applying high voltage. Continuously applying high voltage on DE actuator causes failures such as current leakage and electric breakdown. To overcome the high voltage actuation drawbacks of DE actuators, this paper raises a new actuation method using DE interacting with external elastic structures. Electromechannical instabilities in the DE structure have been harnessed to enhance the performances of the actuator, and to achieve new actuation characteristics, such as soft robotics and bi-stable controlling unit. The analysis is demonstrated based on continuum mechanics, and agrees well with experiment measurements.

9056-22c

An energy approach to characterize the dynamic instability of dielectric elastomer actuators

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In the light of their anticipated use as artificial muscles, analysis of dielectric elastomer actuators (DEA) has been of continued interest over the past decade. While the quasi-static analysis of DEAs is getting mature, relatively a few number of researchers have addressed their dynamic behavior. To this end, this work presents an energy approach to analyze the dynamic instability of homogeneously deformed dielectric elastomer actuator subjected to a suddenly applied voltage. An SDOF model is devised in terms of the thickness-stretch assuming that the elastomer is nearly incompressible. The actuator performs an oscillatory motion till the point of dynamic instability with the period of oscillations increasing with an increase in the applied voltage.

The present approach exploits the energy balance at the point of maximum stretch during an oscillation cycle. At this point; the velocity, and hence the kinetic energy, of the actuator is zero. Therefore all injected electrostatic energy equals to the strain energy stored in the actuator. This condition together with the condition of instability is used simultaneously to arrive at the expressions of maximum stretch and the applied voltage corresponding to the dynamic instability. The approach enables a direct extraction of the aforementioned critical values circumventing the need to perform the time-integration iteratively. A representative case of DEA made up of a Neo-Hookean material is considered for demonstrating the applicability of the proposed approach. The results are compared with those published in the literature. Our predictions of threshold values indicate a close match and also ameliorate the currently available estimates.

9056-23a

Soft generators for sustainable motion-based energy harvesting *(Invited Paper)*

Adrian Koh, National Univ. of Singapore (Singapore) and Institute of High Performance Computing (Singapore)

A dielectric elastomer reversibly transduces between its electrical and mechanical thermodynamic states, allowing it to be used as an actuator, sensor and generator. This talk focuses on the use of dielectric elastomer as a generator (DEG). Due to material non-linearity, electromechanical coupling and complex dissipative processes, realizing the full potential of a DEG remains a challenge. We tackle this challenge on three fronts: First, we use a thermodynamic model to estimate the maximum amount of energy that can be converted. This model enables us to compare and design different DEG systems. Second, we develop loss models based on experimental measurements of viscoelasticity, hysteresis, dielectric losses and current leakage. This model enables us to optimize operating conditions to give the highest conversion efficiency. Third, we design simple experiments that allow repeatable and consistent measurements on the output yield of a DEG. Our theoretical model revealed that DEGs convert energy at a specific energy density of at least an order of magnitude higher than piezoelectrics and electromagnetic generators. Our experiments show that natural rubber converts up to three times more energy than the commonly-used VHB, and is more durable against cyclic operation, less viscous and more efficient. Natural rubber also costs significantly less to produce, paving the way for portable and efficient high-performance generators to be commercialized.

9056-24a

Stack design for portable artificial muscle generators: is it dangerous to be short and fat?

Iain A. Anderson, The Univ. of Auckland (New Zealand); Samuel Rosset, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Thomas G. McKay, The Univ. of Auckland (New Zealand); Herbert R. Shea, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Dielectric elastomer (DE) generators are suited for harvesting energy from low frequencies and high strain natural sources including wind, wave and human movement. The stack configuration, for instance, in which a number of layers of DE membrane are placed one atop the other, offers a robust, compact and solid-state way for arranging the DE material for energy harvesting during heel strike. But the end conditions at top and bottom of a stack can substantially limit its ability to strain.

Using an analytical model for compression of the stack, we have calculated thickness changes in capacitive membranes along the stack for several cylindrical shapes. DE generators that are short and broad will have approximately parabolic profiles with continuous reduction in layer thickness towards the middle. This will result in higher electrical fields toward the middle with greater susceptibility to breakdown. For long, thin DE generator stacks, the outward bulging will be confined to zones at the two ends with a more uniform cylindrical profile in between.

Two design options are offered. One is to place non-capacitive buffer material at the ends where the strains are non-uniform. The buffer material can also serve to reduce overall stiffness associated with bonded ends. A second option is to produce tailor-made stacks: making the layers thickest towards the middle so that when they are compressed they will not incur high field. This could be achieved through printing. Such tailored stacks would be sensible for short and wide designs.

9056-25a

An experimental and numerical approach to understand the effect of the IPMC composition on its sensing and energy harvesting behavior

Barbar J. Akle, Lebanese American Univ. (Lebanon)

Ionic Polymer Metal Composite (IPMC) is an Electo-Active Polymer (EAP) that is well-known for its actuation and sensing behavior. It has been shown that in charge sensing mode an IPMC generates one order of magnitude larger current as compared to piezoelectric materials. However the voltage generated is on the order of couple millivolts, making it less attractive as a sensor and energy harvester. Previous numerical work by the author, demonstrated that increasing the ionic concentration of the ionomer will increase the current and voltage generated by an IPMC. Conversely, the previous study showed that the electrode composition and architecture had minimal effects. This paper will present an experimental investigation of the effect of changing the composition of the ionomer, the cation species, the diluent, and electrode architecture and species on the sensing and energy harvesting behavior. The polymer is characterized using step and sine wave excitation to generate frequency response functions. The response of all IPMC transducers is analyzed and compared to numerical simulations.

9056-26a

Multi-source energy harvester for wildlife tracking

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Sufficient power supply to run GPS machinery and transmit data is the key challenge for wildlife tracking technology. Traditional way of replacing battery periodically is not only time and money consuming but also dangerous to live-trapping wild animals. In this paper, an innovative wildlife tracking device with multi-source energy harvester with advantage of high efficiency and reliability is investigated and developed. A multi-source energy harvester with solar energy harvester, piezoelectric energy harvester and electromagnetic energy harvester is mounted on the “wildlife tracking collar” which will remarkably extend the duration of wild life tracking device as well as various kinds of sensors such as temperature sensor, humidity sensor, etc. Finite Element Analysis approach has been applied to optimally design the dimensions of collar. An electromagnetic energy harvester with flat-spring design has been demonstrated. Prototype of the multi-source energy harvesting collar has been built and tested. The experiment results verify that the proposed multi-source energy harvesting collar can effectively provide sufficient power for animal tracking devices.

9056-27b

Filled liquid silicone rubbers: possibilities and challenges *(Invited Paper)*

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Liquid silicone rubbers (LSRs) have been shown to possess very favorable properties as dielectric electroactive polymers due to their very high breakdown strengths (up to 160 V/um) combined with their fast response, relatively high tear strength, acceptable Young’s modulus as well as they can be filled with permittivity enhancing fillers. However, LSRs possess large viscosity, especially when additional fillers are added. Therefore both mixing and coating of the required thin films become difficult. The solution so far has been to use solvent to dilute the reaction mixture in order both to ensure better particle dispersion as well as allowing for film formation properties. We investigate how the use of solvent influences the properties of the resulting films, such as the tear strength, the Young’s modulus, the dielectric permittivity, the mechanical and dielectric losses, and the electrical breakdown strength. We show that the mechanical properties of the films as well as the electrical breakdown strength can be affected, and that the control of the amount of solvent throughout the coating process is essential for solvent borne processes. Another problem encountered when adding solvent to the highly filled reaction mixture is the loss of tension in the material upon large deformations. These losses are shown to be irreversible and happen within the first large-strain cycle.

9056-29b

Electromechanical response of NCC-PEO composites

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Poly(ethylene oxide) (PEO) has been widely studied as a solid-polymer electrolyte where both the cations and anions can move inside of it under an applied electric field. The motion of these charge carriers in the PEO results in the accumulation of ions close to the electrodes. The inherent size difference between the types of ions causes an unequal volume change between the two sides which translates to an observed mechanical bending. This is similar to electroactive polymers made from conducting polymers. Typically, PEO has a slow response. Some efforts have been given to develop PEO-based polymer blends to improve their performance. In this work, a fundamental study on the electromechanical response is conducted: the time dependence of the electromechanical response is characterized for PEO under different electric fields. Based on the results, a new methodology to monitor the electromechanical response is introduced. The method is based on the frequency dependence of the samples’ dielectric properties. To improve the electromechanical response, the PEO is embedded with piezoelectric nanocrystalline cellulose (NCC). NCC is a biomass derivative that is biodegradable, renewable, and inexpensive. The dielectric, mechanical, and electromechanical properties of the NCC-PEO composites are characterized. It is found that the mechanical and electromechanical properties of the PEO are significantly improved with adding NCC. For example, the composites with 1.5 vol.% of NCC exhibit an electromechanical strain and Young’s modulus that is 25% and 20% higher, respectively, than for PEO without NCC. However, the electromechanical response decreases when the NCC content is high.

9056-30b

Stimuli-responsive hydrogel actuators

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Stimuli-responsive materials capable of performing work by converting an external stimulation into mechanical motion are the frameworks of the evolving field of smart actuators. Stimuli-responsive hydrogels are one example of such materials. Broadly, hydrogels are hydrophilic polymeric networks, in which polymer chains are crosslinked to one another so that the material uptakes large quantity of water without dissolving. Stimuli-responsive hydrogels are known to respond to a variety of external stimuli such as pH, temperature, chemical species, ionic strength and electric field. While hydrogels can exhibit considerably large deformation upon stimulation, most are not mechanically robust enough to sustain an external force. Many actuators and artificial muscles, on the other hand, are required to remain functional under an applied load. Here, a new approach to create a robust pH-responsive hydrogel is described. This hydrogel is employed to investigate the actuation performance and dynamics of pH-responsive hydrogel actuators under different external loads. The actuation results obtained are then analysed using

two different approaches: a thermodynamics approach and a simple mechanical approach.

9056-134b

Electroactive polymers with giant electromechanical response

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Exploiting the molecular and nano-structure engineering, electroactive polymers (EAPs) with giant electromechanical responses have been developed at Penn State. For the field actuated EAPs, a class of defects modified polar-fluoropolymers have been demonstrated to exhibit a high electrostrictive strain, a high energy conversion efficiency, and high elastic energy density (> 1 J/cm3), which has been commercialized by Akema and commercial actuator products have been developed at Novesentis. This talk will briefly review these results. In contrast, the ionic EAPs such as ionic polymer metal composites whose actuation mechanism is based on the excess ion accumulation/depletion at the electrodes, suffer low actuation strain, elastic energy density, and efficiency. On the other hand, the very low operation voltage, often below 5 volts, of i-EAPs is very attractive, compared with very high operation voltage of the field actuated EAPs. In the past several years, we have been investigating approaches to significantly enhance the electromechanical response of i-EAPs. This talk will present the recent works on a class of nano-structure engineered graphene nano-composites that exhibit a high strain response (> 50% strain) with an exceptionally high elastic energy density > 1.5 J/cm3, induced under low voltage (< 5 V) with a high efficiency. These results point out the potential of EAPs in achieving high performance by exploiting nano-structure engineering and their promise for advanced solid state actuator applications.

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9056-31a

An improved electromechanical conversion cycle for optimizing the energy density of dielectric elastomer generators

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Conversion of mechanical energy into electrical energy can be achieved using a dielectric elastomer generator (DEG), a highly compliant variable capacitor constructed from electroactive polymers and stretchable electrodes. During an energy conversion cycle, the performance of the DEG is limited by complex interplays between mechanical characteristics (stiffness, rupture strength) and electrical properties (relative permittivity and breakdown strength) of the dielectric material. Prescribed schemes on how to perform energy conversion using DEGs exist in the literature, however, none fully optimizes the conversion cycle or follows the paths that theoretical analysis indicates maximizing the energy density. We propose a practical method to achieve high energy density of a DEG that can be applied to various mechanical loading schemes. In essence, this method takes into account the changing capacitance of the DEG and then maximizes the electrical energy conversion cycle in the voltage-charge plane, by operating near the material limits. In this presentation, we will first show the proposed electromechanical cycle using analytical modeling, which indicate that the calculated energy density is close to the maximum theoretical prediction (>80%). Secondly, we will present experimental results using an acrylic elastomer that demonstrates the feasibility of this enhanced conversion scheme in a practical situation. Finally, we will describe possible limitations of this approach, which are associated with the intrinsic electromechanical loss characteristics of the dielectric materials themselves.

9056-32a

A bi-directional flyback converter for a dielectric electroactive polymer generator

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During the past few years, Dielectric ElectroActive Polymer (DEAP) has been proven to be a smart material offering new possibilities for energy conversion applications. Indeed, several energy harvesting applications have been presented and numerous articles have been published, where the DEAP generator has been used to harvest energy from energy sources like wave power. However, limited work has been presented so far, where energy harvesting via DEAP generators was accomplished by active power electronic converters, due to the presence of high voltages across the DEAP generator electrodes. In this paper, a bi-directional DC-DC flyback converter with maximum measured step down and up converter efficiency of 86% from 350 V to 1200 V and vice versa is coupled to a ring-shaped DEAP generator which is installed in a horizontal mechanical test rig and both the system energy harvesting efficiency as well as the DEAP energy conversion efficiency are thoroughly documented via numerous experimental results.

9056-33a

High-dielectric elastomeric actuation stress generated in oil immersion

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Dielectric elastomer actuators (DEAs) can produce a large actuation strain (surpassing 100%) like natural muscle. However, these soft actuators can only produces a moderate level of actuation stress not more than 200kPa due to moderate electric breakdown strength. This seriously limits its application to robotic system, such as arm wrestling actuators. To act as artificial muscles for robotic application, DEA needs to generate more force. Enhancement of dielectric strength (greater than 500MV/m) by dielectric oil immersion could possibly enable a larger force generation. According literature, dielectric elastomer actuators are avoided from pull-in instability by pre-stretch. However, dielectric elastomers are eventually subjected to terminal breakdown. Recently, immersion in a dielectric liquid bath was shown to greatly enhance DEA's dielectric strength, beyond 500MV/m. Encouraged by the beneficial effects of dielectric liquid immersion, we developed a membrane DEA (VHB 4905), which is sealed by portable cells of dielectric liquid immersion (Dow Corning Fluid 200 50cSt), for activation under pure shear condition. This oil-celled DEA consists of two cells of dielectric liquid which are attached to completely cover electrode areas of DEA. It can lift up an external deadweight more than 30% strain. In addition, iso-strain tests at 100% strain show that the oil-celled DEA can generate 500kPa actuation stress, 2.5 times higher than 200kPa generated by a DEA in air. Such improvement is attained because of the oil-celled DEAs can sustain an 600MV/m electric breakdown field strength, which is 2.4 times higher than 250MV/ of the DEAs in air. In addition, our design of dielectric liquid cells by means of immersion is very potential to be configured in multilayered DEAs. It is very promising to generate more force if the oil-celled DEAs could be stacked into multi-layered configuration.

9056-34a

Harvesting energy from a water flow through ionic polymer metal composites' buckling

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Several recent efforts have investigated the potential of soft smart materials to harvest energy from fluids. In this context, ionic polymer metal composites have emerged as a valuable material choice for their large compliance and ability to work in wet environments. In this study, we explore the feasibility of energy harvesting from mechanical buckling of IPMCs induced by a steady flow. Toward this objective, we develop a miniature device by integrating IPMC strips in a classical rotary machine design. Our system is composed of a miniature turbine that extracts energy from the fluid, a slider-crank mechanism that converts the turbine rotation into periodic linear motion, and two patterned IPMCs strips clamped at both their ends. We test the device in a laboratory water tunnel and experimentally determine its energy harvesting capabilities, by varying both the shunting resistance and the water speed. To gain further insight into our experimental findings, we adapt the classical theory of post-buckling of inextensible beams along with a lumped circuit model of IPMC sensing. Ultimately, this study demonstrates the feasibility of energy harvesting from patterned IPMC strips through mechanical buckling and develops an experimentally-validated modeling framework for IPMC-based energy harvesting from a steady water flow.

9056-35b

Design of an innovative dielectric elastomer actuator for space applications

Francesco Branz, Francesco Sansone, Alessandro Francesconi, Univ. degli Studi di Padova (Italy)

The capability of Dielectric Elastomers to show large deformations under high voltage loads has been deeply investigated to develop a number of actuators concepts. From a space systems point of view, the advantages introduced by this class of smart materials are considerable and include high conversion efficiency, distributed actuation, self-sensing capability, light weight and low cost. This paper focuses on the design of a solid-state actuator capable of high positioning resolution. The use of Electroactive Polymers make this device interesting for space mechanisms applications, such as antenna and sensor pointing, solar array orientation, attitude control, adaptive structures and robotic manipulators. In particular, such actuation suffers neither wear, nor fatigue issues and shows highly damped vibrations, thus requiring no maintenance and transferring low disturbance to the surrounding structures. The main weakness of such actuator is the relatively low force/torque values available. The proposed geometry allows two rotational degrees of freedom, and simulations are performed to measure the expected instant angular deflection at zero load and the stall torque of the actuator under a given high voltage load. Several geometric parameters are varied and their influence on the device behaviour is studied. Simplified relations are extrapolated from the numerical results and represent useful predicting tools for design purposes. Beside the expected static performances, the dynamic behaviour of the device is also assessed and the input/output transfer function is estimated. Finally, a prototype design and laboratory set-up are presented; the experimental activity aims to validate the preliminary results obtained by numerical analysis.

9056-36b

Towards shear tactile displays with DEAs

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Much research has been done on the development of tactile displays using Dielectric Elastomer Actuators (DEAs). It has been argued that they offer the potential to create low-cost full-page tactile displays, something that is not possible with existing actuator technologies. All research to date has considered tactile elements moving perpendicular to the skin and thus applying a normal force distribution.

In contrast to previous work, we have investigated the use of laterally moving tactile elements that apply shear forces to the skin. Lateral stimulation has previously been used successfully in a piezo-actuated tactile display. The paradigm offers a number of benefits: the areal expansion of DEAs can be exploited directly; the tactile display can be made thinner and with no out-of-plane elements; and bidirectional stimulation is possible, positive and negative strains on the skin can be generated. There is evidence that humans are very sensitive to shear force distributions, and that in some cases a shear stimulus is indistinguishable from a normal stimulus.

We demonstrate that a DEA can generate forces and displacements suitable for a shear tactile display, and present a prototype.

If shear stimulus is to be effectively exploited then an understanding of the primitives of the stimulus is required. These are fundamentally different to those of a normal display. We present different display topologies and analyse possible mechanisms of conveying tactile information, starting from the basic shear force element and outlining minimum requirements for displaying different tactile information types.

9056-37b

Bucky gel actuators optimization towards haptic applications

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An ideal plastic actuator for haptic applications should generate a relatively large displacement (minimum 0.2-0.6mm), force (~50mN/cm2) and a fast actuation response to the applied voltage. Although many different types of flexible, plastic actuators based on electroactive polymers (EAP) are currently under investigation, the ionic EAPs are the only ones that can be operated at low voltage. This property makes them suitable for applications that require inherently safe actuators. Among the ionic EAPs, bucky gel based actuators are very promising. Bucky gel is a physical gel made by grounding imidazolium ionic liquids with carbon nanotubes, which can then be incorporated in a polymeric composite matrix to prepare the active electrode layers of linear and bending actuators. Anyhow, many conflicting factors have to be balanced to obtain required performance. In order to produce high force a large stiffness is preferable but this limits the displacement. Moreover, the bigger the active electrode the larger the force. However the thicker an actuator is, the slower the charging process becomes (it is diffusion limited). In order to increase the charging speed a thin electrolyte would be desirable, but this increases the probability of pinholes and device failure. In this paper we will present how different approaches in electrolyte and electrode preparation influence actuator performance and properties taking particularly into account the device ionic conductivity (which influences the charging speed) and the electrode surface resistance (which influences both the recruitment of the whole actuator length and its speed).

9056-38b

Improvement sensitivity of resistance type single-axis tactile sensor using liquid

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Recently, the tactile sensors with polymer substrate have been widely

implemented in various robotic applications for feedback control based on the contact force measurement because the polymer is flexible in its mechanical property and affordable in price. One of the major research challenges in such sensors is to improve the sensitivity and many studies adapt structures like air gap to make the structure more flexible. These sensors normally have good sensitivity on the limited contact area. However, in case of a larger contact area, the sensor has low performance because the contact force is absorbed by the polymer structure and the thin structure part tends to collapse easily.

In this paper, we propose the resistive type tactile sensor with a liquid pocket. The tactile sensor with polymer substrate has two components which are the sensing element and the structural part. The sensing part is surrounded by polymer (PDMS, Sylgard 184) which is relatively solid. To make the sensor more sensitive, we design the upper part of the sensing element in a shape of semi-cylinder filled with a liquid (Glycerin). When the force is applied to the sensor, the liquid pressure increases and moves the sensing element to deform. The liquid should be not volatile in room temperature and have the heat-resistance. The size of sensing element is 4 x 2 x 1 mm. The sensor can measure the force up to 20N. With the proposed method, we expect the sensor has uniform performance with various contact area of the force.

9056-99

The effect of processing conditions on the crystal structure and electroactive properties of poly(vinylidene fluoride)/ multi-walled carbon nanotubes nanocomposites

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The most common approaches for the fabrication of Poly(vinylidene fluoride)(PVDF)/ multi-walled carbon nanotubes(MWNTs) nanocomposites involve solution crystallization and melting crystallization methods. In this study, PVDF/ MWNTs nanocomposites with varied contents of MWCNTs?up to 0.5wt.%?were prepared via solution crystallized at 80?, solution crystallized at 120? and melting at 200?. The effect of processing conditions on the crystal structure, morphology, dielectric and ferroelectric properties of PVDF with the presence of MWNTs was investigated. A synergetic effect of crystallization temperatures and the concentrations of MWNTs on the crystal phase and crystallinity of PVDF has been observed. Higher crystallization temperatures appeared to be detrimental to the dispersion of MWNTs in PVDF matrix, however, it was advantage to the growth of crystals and leaded to a higher degree of crystallinity. Lower crystallization temperatures favored the dispersion of MWNTs in PVDF matrix, which can effectively promote the formation of polar crystalline beta-phase of PVDF. In addition, MWNTs at relatively low content (< 0.1 wt.%) can disperse well in PVDF matrix in different approaches, resulting in high content of beta-phase and enhancements in dielectric and ferroelectric properties.

9056-100

Electrical actuation properties of epoxy shape memory polymers/reduced graphene oxide paper composite

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Shape memory polymers (SMP) have interesting ability to return from a temporary shape to a permanent shape induced by an appropriate stimulus. SMP composites, which act to improve a certain function, can be developed into multifunctional materials actuated by various methods, such as electricity, heat, light and solution. This study constructs a novel reduced graphene oxide paper enabled SMP composite displayed a good shape memory e?ect in response to applied voltage. The initial thermal decomposition temperature of epoxy SMP reaches 300 oC. The glass transition temperature of epoxy SMP is about 120 oC. The electrical resistivity of reduced graphene oxide paper is only 8.0 m?.cm measured by four-point probe method. Investigation on shape recovery behavior reveals that recoverability of the composite approximated to 100% only taking 5.0 s applied 6.0 V. The temperature distribution and recovery behavior of samples were recorded with infrared video in a shape recovery test. The results show that reduced graphene oxide paper possesses excellent heat conductive properties which can serve as a conductive layer to transmit heat through the polymer. Epoxy shape memory polymers/reduced graphene oxide paper composite is an example of a promising potential in a range of applications as actively moving polymers, which can undergo significant macroscopic deformation in a predefined manner between/among shapes in the presence of an appropriate stimulus. The composite greatly enhance the performance of the SMP and widen their potential applications.

9056-101

Mechanism of strain-induced effect in VHB 4910 by in situ x-ray diffraction and Raman spectroscopy

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Elastomeric films are used in a variety of industrial and prosthetic applications. Phase change memory is a promising candidature for the next generation of non volatile memory devices. The commercially available VBH 4910 elastomeric film that utilizes reversible phase transitions between amorphous and crystalline phases of material and it was reported to be a feasible material to produce muscle-like actuators. The outstanding performance will be obtained when the film is prestretched. Strain induced bond alignment were analysed in both the (uniaxial and biaxial) cases. The electrical and mechanical properties of the film change to the extent that it can only explained by dynamical changes at the molecular level in the elastomer. We present spectroscopic results from experiments on VHB4910 where the elastomer was subjected to several levels of uniaxial and biaxial strain. X-ray diffraction (XRD measurements show structural changes under different levels of stress. Polarization Raman Spectroscopy measurements show that the most changes undergone in the region of the C-H stretch as a function of strain. These changes also indicate that the uniaxial strain and biaxial strain have different effect on the bond alignment (polarization) with strain. Overall, as the order increases with strain, the molecular polarizability of some of the C-H vibrational modes decreases. This change in symmetry of the unstrained versus the ordered is also reflected by a change in fluorescence intensity. All these presented experimental results will be helpful to understand the role of deformation on electronic property of investigated elastomer.

9056-103

Beta-phase poly(vinylidene fluoride) fabrication under droplet drying process

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We confirmed the presence of beta-phase crystals in poly(vinylidene fluoride) (PVDF) under droplet drying process. This study is conducted to investigate beta-phase PVDF formation mechanism in droplet drying process. First, PVDF films are fabricated by drying some droplets on the several types of substrate, in order to prepare the different initial droplet shape on the substrate. Second, their PVDF crystalline structures are

analyzed using x-ray diffraction. As a result, the effect of initial droplet shape on beta-phase PVDF crystal formation is investigated, and the formation mechanism is discussed with present experimental results.

9056-104

Novel encapsulation technique for incorporation of high permittivity fillers into silicone elastomers

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The research on soft elastomers with high dielectric permittivity for the use as dielectric electroactive polymers has grown substantially within the last decade. The approaches can be categorized into three main classes: 1) Mixing or blending in high permittivity fillers, 2) Grafting of high permittivity molecules onto the polymer backbone in the elastomer, and 3) Encapsulation of high permittivity fillers. The approach investigated here is a new type of encapsulation which does not interfere with the mechanical properties to the same content as for the thermoplastic encapsulation. The properties of the elastomers are investigated as function of the filler content and type. The electrical breakdown strength, dielectric permittivity, dielectric loss, conductivity, tear strength, viscous loss, Young's modulus as well as the maximum extensibility are compared to elastomers with the same amounts of high permittivity fillers blended into the elastomer, and it is found that the encapsulation provides a technique to enhance many of these properties.

9056-105

DEAP actuator and its high voltage driver for heating valve application

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In the past decades, energy shortage has gained increasing attention. The highly efficient heating system plays an important role in saving energy. Radiator thermostat is one of the most critical components in state-of-the-art heating system, which can automatically adjust the position of heating valves to control the hot water flow in the pipe according to the ambient environment. Compared to conventional actuators inside the radiator thermostat, DEAP (Dielectric Electro Active Polymer) material based actuator has many advantages, such as high efficiency, noise free operation, remote control availability, etc.

This paper will include three parts of discussion. The first part is the introduction of the heating system and the valve under study as well as the requirements for the DEAP actuator, such as stroke, force, operation frequency range, etc. Based on the demands, the second part will focus on the design of the DEAP actuator for this specific application. The configuration, dimensions and auxiliary mechanical parts of the actuator will be illustrated in this part. The third part will discuss the high voltage driving electronics, including the design of power and control stage, the realization of the high voltage measurement circuit as well as the close loop control.

Finally, the measurement results for individual parts are used to verify the design for each part. In addition, the system level test result is utilized to check the operation state for the whole system.

9056-108

The electrical breakdown of thin dielectric elastomers: thermal effects

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Dielectric elastomer are being developed as actuators, sensors and generators to be used in various applications, such as artificial eye lids1, pressure sensors2 and human motion energy generators3. In order to obtain maximum efficiency, the devices are operated at high electrical fields, which make the likelihood for electrical breakdown large. Hence the performance of the dielectric elastomers is limited by this risk of failure, which is triggered by several factors. Amongst others thermal effects may strongly influence the electrical breakdown strength4.

In this study, we model the thermal breakdown in thin PDMS based dielectric elastomers in order to evaluate the thermal mechanisms behind the electrical failures. The objective is to predict the operation range of PDMS based dielectric elastomers with respect to the temperature at given electric fields. We apply transient nonlinear finite element analysis to predict thermal runaway of dielectric elastomer films. In combination with the modeling, we study the effect of temperature on dielectric properties of different systems of PDMS dielectric elastomers experimentally. Films of PDMS loaded with different percentages of silica and various permittivity enhancing fillers are prepared and analyzed by means of Thermogravimetric Analysis (TGA). In addition, their conductivity and dielectric permittivity are measured as function of temperature. It is found that the electrical breakdown of the materials is strongly influenced by the increase in both conductivity and dielectric permittivity with temperature.

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9056-109

Vacuum packages for MEMS-based sensors

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Vacuum continues to be an enabling environment for electronic devices into the 21st century. Here, examples include infrared IR sensing systems. Out-gassing from surfaces in these systems destroys these controlled ambient over time days to years. MEMS and MOEMS are not immune to these issues. Most of MEMS based sensors are sensitive to the operating pressure, the partial pressure of water vapor in the package, or both. For example, infrared sensors need to operate in a pressure 10-3 Torr in order to be thermally isolated from the outside world and maintain adequate sensitivity. The situation is further complicated by the need for high degrees of hermeticity leak rates on the order of 10-12 atm-cc/s and the lack of space to mount getters to control the contaminants in the package. Hermeticity is currently a significant issue in the microelectronics packaging field as a whole. Hermetically packaging MEMS devices in a reliable and economical manner is a topic of great interest to the MEMS community. The development of MEMS technology has reached a point where the packaging of the device is proving to be more difficult than the actual device development itself. Many development groups are finding their efforts stymied at this point, and interest in MEMS packaging and related topics is at a high level. In

this study, among various and significant factors such as structural and geometric design of a device, considering optical design, thermal design, electrical design, mechanical design, and process design, fabrication of the device, design and fabrication of a circuit, device analysis, property measurement, design and fabrication of optical system, and design and fabrication of package module on R&D for MEMS based opto-electro-thermo-mechanical device, we will address a methodology for design, fabrication, and analysis of MEMS based infrared sensor array packaging. Also, ultimate type of wafer level packaging will be introduced in a view point of design factors and structural differences compared with on-going metal packaging

9056-110

Controlled active motion of metallic nanostructures on a stretchable electroactive polymer

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Electroactive polymers (EAPs) which have highly efficient actuation properties with a large area strain in an electric field are prominent material with potential applications in various research fields such as electrical sensors, compact actuators, artificial muscles and micro robotics. Dielectric elastomer has shown the abilities such as fast responses, large strain, durability, and stability which can be applicable as an active moving substrate. Here, we fabricate highly ordered multiscale metal array on stretchable electroactive polymer for generation of the active motion of metallic nanostructures. Actuation of dielectric elastomers between compliant electrodes under high voltages induces stretchable/shrinkable movements of the surface leading the motions of multiscale metallic structures formed by nanotransfer printing process. Stamping process based on soft lithographic approach is an efficient method for making a multiscale metal array on stretchable polymer without damages of thin dielectric substrate. The movement of multiscale metallic structures is attractive phenomenon with its advanced geometrical effect on several applications such as active structural colors, adjustment of surface functions, microfluidics, actuators and optical devices. Active surface with moving multiscale metallic patterns can be applicable to tune the geometrics of multiscale structure for assigning various surface functions on the dielectric elastomer.

9056-111

PDMS/MWCNT nanocomposite actuators using silicone functionalized multiwalled carbon nanotubes via nitrene chemistry

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We demonstrated that covalently functionalized multiwalled carbon nanotubes (MWCNT) with a silicone copolymer via nitrene chemistry can be used as efficient conductive fillers for the silicone dielectric elastomer actuators. The MWCNTs were covalently functionalized with poly(azidopropylmethyl)-co-(dimethylsiloxane) (silicone-N3) bearing an azide group through a nitrene addition reaction. The incorporation of a small amount of the uniformly silicone grafted MWCNTs (silicone-g-MWCNTs) in silicone dielectric elastomer strongly enhanced the mechanical, dielectric, and electromechanical properties of the resulting nanocomposites. This reinforcing effect is attributed to the homogeneous dispersion of silicone-g-MWCNTs in the silicone elastomer matrix due to the large degree of compatibility between the matrix and the passivation layers of the functionalized MWCNT.

9056-112

Inhomogeneous deformation of circular dielectric actuator: simulation and experiment

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A variety of possible configurations have been developed to exploit the capabilities of the dielectric elastomers. Circular dielectric actuator is a simple flexible structure that can be used in many areas, for example, it can be employed to adjust the properties of the optical elements. The configurations of circular dielectric actuators range from one active dielectric region to multiple active dielectric regions. When the active dielectric regions subject to a voltage, they will expand and compress the electrode-less regions. The circular actuator in this work consists of two electrode regions and two electrode-less regions. One electrode-less region is an annular elastomer sandwiched between the inner dielectric circle and the middle dielectric annulus. The other electrode-less region is between the middle dielectric annulus and the rigid frame. We study the properties of the actuator based on the ideal dielectric model and obtain the relationship between the applied voltage and the deformation. Additionally, the inhomogeneous deformation of the circular actuator has been investigated both theoretically and experimentally and a good correlation is achieved. The strategy presented here is generic and can be applied to other circular configurations with multiple regions. The results may contribute to the use of circular dielectric actuators in advance.

9056-113

Autofocus fluid lens device construction and implementation of modified IPMC membrane actuators

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Autofocus fluid lens device as example developed by Phillips based on water/oil interfaces forming a spherical lens by the meniscus of the liquid that can be switched by applying high voltage to change from convex to concave divergent lens. In this work we construct a device to evaluate the performance of membrane actuators based on EAP in later design applicable for autofocus fluid lens application. The membrane with hole in the middle separates the oil phase and electrolyte phase, forming a meniscus in the middle of the membrane between oil/electrolyte. If the membrane actuator shows certain force and displacement the meniscus between oil and electrolyte will change their form between concave and convex, applicable as fluid lens. Ionic polymer metal composites (IPMC) are applied in this work to investigate how the performance of the membrane actuator takes place in water, electrolyte and in combination of electrochemical deposited conducting polymers. The goal of this work is to inhibit the typical back relaxation of IPMC actuators and made them suitable at low voltage (± 0.7 V) in fluid lens operation.

9056-114

Electrochemomechanical deformation (ECMD) of PPyDBS in free standing film formation and trilayer design

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An investigation is reported into the electrochemomechanical deformation (ECMD) of polypyrrole (PPy) doped with dodecylbenzenesulfonate (DBS) in the form of freestanding films and as depositions on conductive

substrates (chemical fixed PEDOT) based on PVdF. Linear conducting polymer (CP) are difficult to arrange in lamellar designs, therefore, several attempts have been made in recent years to obtain fiber actuators or chemically oxidized CP in flexible interpenetrated network (IPN) matrix of polyethylene oxide and polybutadiene to obtain linear actuation properties. An obvious drawback of this approach is the decreased strain caused by inclusion of the more restrained passive material. The goal of this work is to try the opposite approach – to achieve linear actuation starting from a typical trilayer bending actuator design with a stretchable middle layer. To allow evaluation of the proposed design, commercially available polyvinylidene fluoride (PVdF) membranes were chosen as model material. For bending trilayer functionality, electronic separation of both electrode layers is essential, but in order to obtain linear actuation, the CP layers on either side are connected to form a single working electrode. The samples were investigated by electrochemical methods (cyclic voltammetry, square wave potentials) in 4-methyl-1,3-dioxolan-2-one (propylene carbonate, PC) solution of tetrabutylammonium trifluoromethanesulfonate (TBACF3SO3).

9056-115

Leakage current of a charge-controlled dielectric elastomer

Junshi Zhang, Hualing Chen, Junjie Sheng, Lei Liu, Xi’an Jiaotong Univ. (China)

The performance of a dielectric elastomer membrane is remarkably affected by dissipation, particularly the leakage current. Based on a charged-controlled dielectric elastomer configuration, this paper presents a theoretical study about the effect of leakage current on the performance of a dielectric elastomer membrane subject to a combination of mechanical force and polarization charge. It is found that when the mechanical force is static, the membrane may reach a state of equilibrium. The effect of leakage current on the static performance is that the equilibrium position of stretch reduces and the stress increases. When the mechanical force is alternating, the membrane will resonate at multiple frequencies. The study result indicates that the leakage current can increase the natural frequency and reduce equilibrium position of stretch of the dielectric elastomer.

9056-116

Experimental investigations on energy harvesting performance of dielectric elastomers

Yong-Quan Wang, Xuejing Liu, Huanhuan Xue, Hualing Chen, Shuhai Jia, Xi’an Jiaotong Univ. (China)

In this paper, the emerging technology of energy harvesting based on dielectric elastomers (DE), a new type of functional materials belonging to the family of Electroactive Polymers (EAPs), is presented with emphasis on its performance characteristics and some key influencing factors. Starting from the material’s hyperelastic constitutive relations and its basic electromechanical coupling model, the balance behaviors of the mechanical and electrical stresses in energy harvesting cycle, as well the maximum electrical energy to be harvested, are systematically compared and discussed, for different material deformation modes (uniaxial stretching, biaxial stretching, and pure shear) and different electrical boundaries (constant charge, constant voltage, and constant electric field). Then, based on this, the effects of other control parameters, i.e., the material’s pre-stretch, its maximum stretch, the ratio of biaxial stretches, and the bias voltage (polarization charge), are further analyzed under certain mechanical and electrical constraints. Meanwhile, using the commercial elastomers of VHB 4910 (3M, USA), a tapered DE generator is designed and fabricated. In the constant charge (open-circuit) condition, a series of experimental tests for the device’s energy harvesting properties are then performed at different pre-stretch ratios, stretch amplitudes (displacements), and the bias voltages. It can be concluded the influence laws of the above factors demonstrated by experimental results have good consistent with those obtained from the theoretical analysis. This study is expected to provide a helful guidance for the design and operation of practical DE energy harvesting devices/systems.

9056-117

Effect of temperature on the electric breakdown strength of dielectric elastomer

Lei Liu, Hualing Chen, Junjie Sheng, Junshi Zhang, Xi’an Jiaotong Univ. (China)

DE (dielectric elastomer) is one of the most promising artificial muscle materials for its large strain over 100% under driving voltage. However, to date, dielectric elastomer actuators (DEAs) are prone to failure due to temperature-dependent electric breakdown. Previously studies manifest that the electrical breakdown strength mainly relate to the temperature-dependent elasticity modulus and permittivity of dielectric substances. This paper investigates the influence of the ambient temperature on the electric breakdown strength of VHB 4190 membrane. Firstly, the electric breakdown experiment of the DE membrane is conducted at different ambient temperatures. And then based on the Stark–Garton electromechanical breakdown model, we obtain the predictions on the electromechanical breakdown strength of VHB4910 at various temperatures by introducing the values of the permittivity and the elasticity modulus earlier tested under different temperatures. Finally, the comparisons between the experimental results and the predictions of the temperature-dependent breakdown strength are presented, and they displayed an excellent consistency.

9056-118

Comparison of plasma treatment and sandblast preprocessing for IPMC actuator

Chi Zhang, Hualing Chen, Yanjie Wang, Yong-Quan Wang, Shuhai Jia, Xi’an Jiaotong Univ. (China)

As a new kind of ionic-driven smart materials, IPMC (ionic polymer metal composites) is normally fabricated by depositing noble metal (gold, platinum, palladium etc) on both sides of base membrane (Nafion, Flemion etc) and shows large bending deflection under low voltage. In the process of fabricating IPMC, surface roughening of base membrane has a significant effect on the performance of IPMC. At present, there are many ways to roughen the base membrane, including physical and chemical ways. However, few researchers devote themselves to explain how the roughening ways affect the performance of IPMC. In this paper, we analyze the effects of different surface treatment time by plasma etching and sandblast way on surface resistance and dielectric constant of IPMCs fabricated by the treated base membranes. Meanwhile, the chemical elements on the surface of the base membrane are checked by XPS. Experimental results show that the base membrane treated by plasma etching displays uniform surface roughness, consequently reducing IPMC’s surface resistance effectively and forming more uniform and homogeneous external and penetrative electrodes. However, due to the use of reactive gas, the plasma treatment leads to complex chemical reaction on Nafion surface, changing element composition and material properties and resulting in the performance degradation of IPMC. And sandblast way should be adopted and improved without any changes on element and material structure.

9056-119

Control of ionic polymer-metal composites actuators with cellular actuator method

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Ionic polymer-metal composite (IPMC) is one of the electro-active polymer materials which respond to electric stimuli with shape change. IPMC actuators can be activated with simple driving circuit and common control approach; however, dynamic characteristics change from environmental conditions such as the temperature or humidity. The output force of IPMC is very small, and the stress relaxation exists depending on the type of the counter-ions in the electrolyte. Therefore, it is desirable to construct robust controllers and connection of multiple actuator units to obtain stable and large output force.

In this study, we apply a control method for cellular actuators to solve above problems. The cellular actuator is a concept of actuators which consist of multiple actuator units. The actuator units connect in parallel or series, and each unit is controlled by distributed controllers, which are switched ON/OFF state stochastically depending on the broadcast error signal which is generated in the central controller.

In this paper, we verify the control performance of the cellular actuator method through numerical simulations. In simulations, we assume that one hundred units of IPMC connected in parallel, the output force is controlled to the desired value. The control performance is investigated in the case of some mixed ratio of units whose counter-ions are Sodium (Na) ion or Tetraethylammonium (TEA). As a result of simulation, it was confirmed that the tracking performance is improved by combining the fast response actuator units of Na ions and the large output actuator units of TEA ions.

9056-120

Optimized deformation behavior of a dielectric elastomer generator

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Dielectric elastomer generators (DEGs) produce electrical energy by converting mechanical to electrical energy. Efficient operation of multilayer DEGs requires homogeneous deformation of each single layer. Internal and external influences like supports may cause an inhomogeneous deformation and hence negatively affect the amount of the generated electrical energy. Optimization of the deformation behavior leads to improved efficiency of the DEG and consequently to higher energy gain. In previous works a numerical simulation model of a dielectric elastomer generator is developed using the FEM software ANSYS. A previous comparison with electro-mechanical characterization results of the real DEG shows the validity of the derived numerical simulation model. In this work the optimization of the deformation behavior of the DEG is carried out using the developed numerical simulation model of the DEG. At first, the support structure of one multilayer DEG module is optimized so that a homogenous deformation of each single layer is achieved. Based on these results, a stack of modules is simulated. The support of the whole stack is optimized regarding an unrestricted expansion of each module in radial direction during compression in vertical direction. In addition, the support structure between the DEG modules is optimized to reach the maximum deformation of each module. With the achieved deformation behavior the maximum electrical energy from each module and consequently from the whole configuration can be harvested regarding the optimized support structures. The optimization results are validated by measurements with a real stack of DEG modules.

9056-121

Dynamic performances of silicone dielectric elastomer actuators with bi-stable buckled beams

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In the present work we examine means of altering the dynamic performance of single-layer, large-scale dielectric elastomer planar actuators with bi-stable buckled beams, i.e. slender beams, compressed beyond buckling and mechanically coupled with the elastomer actuator. Snap-through of the bi-stable beam is triggered by actuator activation. We describe the influence of physical parameters, material, thickness and pre-stretch ratios of the dielectric with realistic clamped boundary conditions. We develop a reliable procedure to design bi-stable elements, considering several configurations. Finally, we produce prototype actuators and measure their performances, in order to prove beneficial effects of bi-stable elements on dynamic actuation response.

9056-122

Dielectric elastomer Bending actuator: experiment and theoretical analysis

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Dielectric elastomer is a kind of smart soft material that has many advantages such as large deformation, fast response, light weight, easy fabrication, etc. Subject to a high voltage, dielectric elastomer film will deform sustainably. These features make dielectric elastomer a suitable material for actuators. A bending actuator of dielectric elastomer is discussed in this paper. An actuator based on dielectric elastomer that can bend when subject to a high voltage is fabricated. A theoretical model of dielectric elastomer bending actuator is established. The initial deformation and bending deformation of bending actuator is formulated based on thermodynamics theories. Most parameters in these formulas can be obtained from fabrication process or test data. Theoretical prediction using these parameters can explain the experimental phenomena well. Also, the allowable area of bending actuator is determined considering several failure models including electromechanical instability, electrical breakdown and tensile rupture.

9056-123

The influence of polyurethane type on the electrostrictive behavior

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The electromechanical behavior of thermoplastic elastomer polyurethane (TPE-PU) is investigated under the effects of urethane type (ester and ether-types) and softehard segments at various electric field strengths and temperatures. The highest dielectric constant, electrical breakdown strength, and specific conductivity belong to the ester-type polyurethane (LPR matrix), while the lowest values are obtained from the ether-type polyurethane composing predominantly with the soft-segment (E 80A matrix). Under the electric field strength in the range between 0 and 2 kV/mm, the LPR matrix attains the storage modulus sensitivity (∆G?/G?0) up to 2 at 2 kV/mm. For the temporal response, the polyurethanes behave with good reproductively (number of cycles >105 times) and with very good recoverability. The steady state behavior can be attained at the first actuation and at the electric field strength of 1 kV/mm. Furthermore, the storage modulus (G?) shows linearly negative responses with increasing temperature. In the deflection experiments, the deflection distance

and the dielectrophoresis force increase monotonically with increasing electric field strength. All of the TPE PU possesses very fast response times for activation (<10 s.) and deactivation (<5 s.). TPE-PU material is systematically shown here to be a potentially good actuator material with high efficiency based on the electrostrictive performance data obtained.

9056-124

Effect of electric field and degree of crosslinking on stress relaxation behavior of gelatin hydrogels: time-electric field superposition

Thawatchai Tungkavet, Anuvat Sirivat, The Petroleum and Petrochemical College (Thailand); Nispa Seetapan, National Metal and Materials Technology Ctr. (Thailand); Datchanee Pattavarakorn, Chiang Mai Univ. (Thailand)

An investigation has been conducted on stress relaxation functions and the corresponding relaxation time distribution functions of gelatin hydrogels for the effects of degree of crosslinking and the applied electric field strength. Uncrosslinked and crosslinked gelatin hydrogels were prepared by adding a glutaraldehyde solution into a gelatin solution followed by a casting method. The characteristic relaxation time can be estimated by three methods; KWW; the dynamic crossover; and the relaxation time distribution spectrum H(?). For the uncrosslinked, 3 %v/v crosslinked and 7 %v/v crosslinked gelatin hydrogels, the relaxation times decrease with increasing degrees of crosslinking and the applied electric field strengths. This is due to the increase in the molecular connectivity that promotes the capability of the stress relaxation process. The experimental shift factors can be thus obtained from either the stress relaxation functions or the storage and loss moduli. Both approaches yield numerically the same shift factor values which successfully allow the time-electric field superposition of various related functions.

9056-125

Tactile feedback to the palm using arbitrarily shaped DEA

Holger Moessinger, Henry Haus, Helmut F. Schlaak, Technische Univ. Darmstadt (Germany)

Tactile stimulus enhances user experience and efficiency in human machine interaction by providing information via another sensory channel to the human brain.

DEA as tactile interfaces have been in the focus of research in recent years. Examples are (vibro-) tactile keyboards or braille displays. These applications of DEA focus mainly on interfacing with the user's fingers or fingertips only – demonstrating the high spatial resolution achievable with DEA.

Besides providing a high resolution, the flexibility of DEA also allows designing free form surfaces equipped with single actuators or actuator matrices which can be fitted to the surface of the human skin. The actuators can then be used to provide tactile stimuli to different areas of the body, not to the fingertips only.

Utilizing and demonstrating this flexibility we designed a free form DEA pad shaped to fit into the inside of the human palm. This pad consists of four single actuators which can provide e.g. directional information such as left, right, up and down.

To demonstrate the value of such free form actuators we manufactured a PC-mouse using 3d printing processes. The actuator pad is mounted on the back of the mouse, resting against the palm while operating it. Software on the PC allows control of the vibration patterns displayed by the actuators. This allows helping the user by raising attention to certain directions or by discriminating between different modes like "pick" or "manipulate".

Results of first tests of the device show an improved user experience while operating the PC mouse.

9056-126

IPMC electrodes with platinum nanothorn assemblies: effects on the electromechanical transduction

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Ionic polymer-metal composites (IPMCs) have become increasingly important as soft actuators and sensors for use in underwater biomimetic robotics and medical applications. Herein, a novel nanostructured Pt electrode surface design of IPMC is reported. The synthesis techniques were developed to control and manipulate the surface structure of Pt electrodes through electroless plating process. By carefully controlling the synthesis parameters, IPMCs with different electrode surface profiles were fabricated. The changes in the electrode surface morphology and the resulting effects on the material's electromechanical, electrochemical and mechanical properties were examined and analyzed. The results show that an appropriate control of the synthesis parameters of electroless plating leads to the formation of platinum nanoparticles with sharp tips and edges – called Pt nanothorn assemblies – at the polymer/electrode interface. The experiments demonstrate that the formation and growth of Pt nanothorn assemblies at the electrode interface increases considerably the total transported charge during the transduction, thereby increasing significantly the displacement and blocking force output of IPMC. An improvement of 3–5 times in the mentioned electromechanical properties was observed, depending on the input voltage and frequency used.

9056-127

Evaluation of encapsulating coatings on the performance of polypyrrole actuators

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Conjugated polymer actuators are electroactive materials capable of generating force and movement in response to an applied external voltage. Many potential biomedical and industrial applications require these actuators to operate in a liquid environment. However, immersion of uncoated conducting polymer actuators in non-electrolyte liquids greatly reduces their operating lifetime. Here, we demonstrate the use of spray coating as an effective and simple method to encapsulate polypyrrole (PPy) tri-layer bending actuators. Poly(styrene-b-isobutylene-b-styrene) (SIBS) was used as an encapsulating, compliant spray coating on PPy actuators. A significant enhancement in actuator lifetime in both air and water was observed by encapsulating the actuators. The change in stiffness and reduction in bending amplitude for coatings of different thickness was studied. A simple beam mechanics model describes the experimental results and highlights the importance of coating compliance for actuator coatings. The model may be used to evaluate other possible encapsulating materials.

9056-128

Extrusion printing of ionic-covalent entanglement hydrogels with high toughness

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Three-dimensional (3D) printing of hydrogels has recently been investigated for use in tissue engineering applications. One major limitation in the use of synthetic hydrogels is their poor mechanical robustness but the development of ‘tough hydrogels’ in conjunction with additive fabrication techniques will accelerate the advancement of many technologies including soft robotics, bionic implants, sensors and controlled release systems. Here we demonstrate that ionic-covalent entanglement (ICE) gels can be fabricated through a modified extrusion printing process that facilitates in situ photopolymerisation. The rheological properties of alginate/acrylamide hydrogel precursor solutions were characterised to develop formulations suitable for extrusion printing. A range of these printed hydrogels were prepared and their mechanical performance and swelling behaviour evaluated. ICE gels exhibit a remarkable mechanical performance because ionic cross links in the biopolymer network act as sacrificial bonds that dissipate energy under stress. The printed ICE gels have a work of extension 260 ± 3 kJ/m3. Swelling the hydrogels in water has a detrimental effect upon their mechanical properties, however swelling the hydrogels in a calcium chloride solution as a post-processing technique reduces the effects of swelling the hydrogels in water. The integration of the modified extrusion printing process with existing plastic 3D printing technologies will allow for the fabrication of functional devices including actuating devices.

9056-129

Dielectric elastomer based active layer for macro-scaled industrial application in roto-flexographic printing

Fulvio Pinto, Michele Meo, Univ. of Bath (United Kingdom)

Dielectric Elastomer based active layer for macro-scaled industrial application in roto-flexographic printing.

The use of dielectric elastomer (DE) for the realisation of new generation actuators has attracted the interest of many researchers in the last ten years due to their high efficiency, a very good electromechanical coupling and large achievable strains [1-3]. Although these properties constitute a very important advantage, the industrial exploitation of such systems is hindered by some manufacturing issues [4] and by the high voltages required for the actuation that could potentially constitute also a risk for the operators.

In this work we present a DE based active layer that can be used to interlock different macro-scaled parts of industrial equipment for roto-flexographic printing without the need of any mechanical devices, reducing manufacturing costs and enhancing the reliability of the connection. Moreover, the specific configuration of the system requires the driving voltage to be applied only in the mounting/dismounting step thus lowering further the operative costs without posing any threat for the workers.

Starting from the industrial requirements, a complete thermo-mechanical characterisation using DSC and DMA was undertaken on acrylic elastomer films in order to investigate their behaviour under the operative frequencies and solicitations. Validation of the active layer was experimentally evaluated by manufacturing a DE actuator controlling both prestrain and nature of the complaint electrodes, and measuring the electrically induced Maxwell strain using a laser vibrometer to evaluate the relative displacement.

Results from the tests showed a compressive strain along the z-axis of more than 15% of the initial length when 3000V are applied on the two faces of the actuator, however by using DC-HVDC convertors the input voltage required to fed the system is between 10 and 15 V for each convertor.

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9056-130

Dielectric elastomer bimorph actuator

Fan Liu, Jinxiong Zhou, Ling Zhang, Yin Wang, Na Ni, Xi’an Jiaotong Univ. (China)

With excellent performance parameters such as large and reversible elastic deformation, short response time, high energy density, good flexibility and high efficiency, high reliability and high actuation pressure, dielectric elastomer (DE) is widely study and used in many types of intelligent actuators.

In this paper, we demonstrated to make a DE bimorph , as the dielectric elastomer actuator , capable of a large bending. The bimorph consists of an active layer, made of VHB elastomer, and a passive layer. Both of the two layers are rectangular strips, about 20mm x 10mm x 0.2mm, and adhesive with the carbon grease, which used as the soft electrode. By applying a voltage, active layer induces strain to bend the passive layer, so the function of the actuator is achieved. Mathematical models about the function of applied voltage and induced strain of the bimorph are proposed. And the related experiment result also shows the similar trend that the second order relationship of the voltage and bending deflection. Hence, this study can be further used in taking place of some aircraft parts, to improve the efficiency of the aircraft.

9056-131

Compliant liquid metal electrodes for dielectric elastomer actuators

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This work presents a liquid metal compliant electrode to be used with electroactive polymers (EAPs) for dielectric elastomer actuators (DEAs). DEAs are favorable for soft-matter applications where high efficiency and response times are desirable. A consistent challenge faced during the fabrication of these devices is the selection and subsequent implementation of electrode material. While a variety of designs have been demonstrated such as through the use of conductive rubbers and greases, thin metallic strips and carbon products, all have significant and often intrinsic shortcomings (e.g. low conductivity, hysteresis, incapability of large deformations and complex fabrication requirements). The liquid metal alloy eutectic Gallium-Indium (eGaIn) is a promising alternative to existing compliant electrodes, having both high conductivity and complete flexibility. The liquid electrode itself adds no resistance to bending or stretching of the DEA, though it must always be contained in an elastomer membrane. This research establishes a straightforward and effective method for quickly depositing eGaIn electrodes, which can be adapted for batch fabrication, and demonstrates the successful

actuation of sample curved cantilever elastomer actuators implementing them. Preliminary data of repeatable actuator deflection in response to a voltage proves the viability of this approach. As with the vast majority of electrostatically actuated elastomer devices, the voltage requirements for these curved DEAs are still quite significant. However, the ease and speed with which this method can be implemented to produce such actuators suggest that the development of a more electronically efficient device within a reasonable time frame is realistic and worthwhile.

9056-132

An investigation of electrochemomechanical actuation of conductive polyacrylonitrile (PAN) nanofiber composites

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No Abstract Available

9056-133

Design and fabrication of an IPMC-embedded tube for minimally invasive surgery applications

Jiayu Liu, Yanjie Wang, Chi Zhang, Dongxu Zhao, Hualing Chen, Dichen Li, Xi'an Jiaotong Univ. (China)

Minimally Invasive Surgery (MIS) is receiving much attention for a number of reasons, including less trauma, faster recovery and enhanced precision. The traditional robotic actuators do not have the capabilities required to fulfill the demand for new applications in MIS. Ionic Polymer Metal Composites (IPMCs), one of the most promising smart materials, have extensive desirable characteristics such as low actuation voltage, large bending deformation and high functionality. Compared with traditional actuators, IPMCs can mimic biological muscle and are highly promising for actuation in robotic surgery. In this paper, a new approach which involves molding and integrating IPMC actuators into a soft silicone material to create an active actuating tube capable of multi-degree-of-freedom motion is presented. First, according to the structure and performance requirements of the actuating tube, two kinds of IPMC actuators have been implemented: the conventional IPMC strip actuators and the biaxial bending IPMC actuators fabricated by using casting method with different cross sections. An assembly based fabrication process was used to bond IPMC strip actuators and biaxial bending IPMC actuators with silicone using molds, respectively. Then the silicone was cured at a suitable temperature to form an IPMC-embedded tube capable of actuation. The IPMC-embedded tube can generate multi-degree-of-freedom motion by controlling each IPMC actuator. Furthermore, the basic performance of the actuators was analyzed, including the output force, the displacement and the response speed. The performance of IPMC-embedded tubes was optimized by utilizing finite element analysis software and IPMC actuators with different dimensions and distributions. Finally, we discuss and compare the theoretical analysis with the experimental results. Experimental results indicate that IPMC-embedded tubes based on IPMC actuators bonded with silicone material are promising for applications in MIS.

9056-135

Sequential growth and monitoring of a polypyrrole actuator system

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Electroactive polymers (EAPs) have emerged as viable materials in sensing and actuating applications, but the capability to mimic the structure and function of natural muscle is increased due to their ability to permit additional, sequential synthesis steps between stages of actuation. Current work is improving upon the mechanical performance in terms of achievable stresses, strains, and strain rates, but issues still remain with actuator lifetime and adaptability. This work seeks to create a bioinspired polymer actuation system that can be monitored using state estimation and adjusted in vivo during operation. The novel, time-saving process of sequential growth was applied to polymer actuator systems for the initial growth, as well as additional growth steps after actuation cycles. Synthesis of conducting polymers on a helical metal electrode directs polymer shape change during actuation, assists in charge distribution along the polymer for actuation, and as is described in this work, constructs a constant working electrode/polymer connection during operation which allows sequential polymer growth based on a performance need. The polymer system is monitored by means of a reduced-order, state estimation model that works between growth and actuation cycles. In this case, actuator stress is improved between growth cycles. The ability for additional synthesis of the polymer actuator not only creates an actuator system that can be optimized based on demand, but creates a dynamic actuator system that more closely mimics natural muscle capability.

9056-136

Modeling and experimental investigation of the IPMC electrodes

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We theoretically predict and experimentally investigate the electrical properties of the electrode of ionic polymer-metal composites (IPMCs). A microstructure model of the electrode and the model of the current in the polymer membrane were developed. By combining the physics of the polymer membrane and the electrode, the model of the surface electrical potential of the IPMC was proposed. Experiments were conducted to test the electrical characteristics of the electrode and validate the model. The results demonstrate that the theoretical model can accurately predict the resistance, capacitance, and surface electrical potential of the IPMC electrode under external oscillation. Based on the model, parametric research was done to study the impact of the parameters on the IPMC electrode properties.

9056-137

Characterization of close-loop performance of double drive modes unimorph deformable mirror

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Unimorph deformable mirrors are attractive in adaptive optics system due to their dvantages of simplicity, compact, low cost and large stroke. In this paper, a double drive modes unimorph deformable mirror is discussed, which comprises a 100 ?m thick PZT layer and a 200 ?m thick silicon layer. This deformable mirror (DM) can achieve two different directions deformation of concave and convex driven by only positive voltage. The dual direction maximum defocus deformations are -14.3 ?m and 14.9 ?m. The close-loop performance of this DM is also tested in an experimental adaptive optics system based on Hartman-Shack wavefront sensor. In experiments, the DM is controlled by the steepest descent algorithm (SD) to corrected the aberrations in a close-loop manner. The ability of this DM of correction for the system aberration and

reconstruction for the low order Zernike mode aberration is tested. The root mean square (rms) value of the system aberration after close-loop correction is about 20 nm. The reconstruction results for most low order Zernike mode aberrations have a relative error less than 10%.

9056-138

A dielectric elastomer balloon actuator

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Dielectric Elastomer is a new kind of smart material, capable of transforming electrical energy to mechanical energy or vice versa. Considering its outstanding attributes such as large deformation, light weight, fast response and low cost, dielectric elastomer is promising to act as actuators and generators in mechanical and biology engineering in the future. To achieve large deformation, however, mechanical prestretch is required to bend the voltage path to avert electromechanical instability and electric breakdown, which belong to the failure modes of dielectric elastomer. All of the current methods of providing prestretch such as spring [1], mass and fibers [2] need a special rigid mechanism. Inspired from air balloon, to achieve fully soft body, the dielectric elastomer is made into a hollow sphere with high-pressure air inside which can achieve the required prestretch, and at the same time avoid troublesome rigid mechanisms.

The operation is as follows: Air is inflated into a dielectric elastomer balloon to achieve a prestretched equilibrium state with voltage-off, and then voltage is applied on the balloon. Due to the inside high-pressure air, mechanical stress will appear inside the dielectric elastomer. This mechanical stress will provide prestretch, avert electromechanical instability and postpone electric breakdown. The performance of the balloon actuator depends on initial pressure before voltage applied, the ratio of radius to thickness of the balloon, and material properties, etc. Theoretical simulation demonstrates that the deformation range would be pretty large for actuators, up to more than two times its volume before voltage applied. In order to improve the performance of proposed actuator, structural optimization technique can be elaborated to find the optimal shape or topology of fully soft balloon dielectric elastomers.

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9056-139

Intelligent forceps using highly twisted actuator

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Minimally invasive surgery is a progressive field of study that helps surgeons to perform fast, complex and high precision surgery by means of teleoperated robotic systems. The cost of having a complete robotic surgical instrument is extremely expensive that only limited number of hospitals could afford them. However, reducing dexterity of surgeons and lack of haptic perception in conventional mechanical forceps not only affect surgical operation but also increase the threat of side effects including tissue trauma due to excessive applied pressure.

Newly developed guest filled twisted carbon nanotube yarn shows high force and large stroke tensile actuation. Based on this design a low-cost high stress and strain thermal polymer fiber with great work-density has been studied to use as an actuator to provide the desired force for grasping tissue in an intelligent forceps. To activate this thermal actuator, the temperature of polymer fibers is increased through the process of Joule heating

Two sets of antagonistic actuators actively control the jaws and provide faster response time, first set for opening and second one for closing the jaws. The spring characteristic of polymer actuator placed the jaws at fully closed position. When one set of actuators is activated to open the jaws the other set works as a passive spring to close it. Experimental findings show that the amount of force of this passive spring varies depending on the jaw angle from 3 Newtons for fully opened to 1 N for near closed position when only one set is deactivated. Actuation of the second set increases more than doubles the force generated. The force requirements for this device are approximately 10 N. The amount of force should be significantly increased by using a thicker actuator and increasing the number of actuators. This work is in progress.

The required displacement for opening and closing the jaws is 3 mm. This displacement requirement is readily provided by the 10 cm long actuators which can achieve 20% strain.

9056-39a

Novel dielectric elastomer sensors for compression load detection *(Invited Paper)*

Holger Böse, Fraunhofer-Institut für Silicatforschung (Germany)

Beside various applications in actuation and energy conversion, dielectric elastomer films can also be used as mechanical sensors for the detection of stretch and associated stress. However, under compression load onto the elastomer film, the measurable change of the capacitance is very limited, due to the extreme aspect ratio of thin films and the volume incompressibility of elastomers. In this paper, novel approaches for dielectric elastomer sensors (DES) with strongly enhanced sensitivity to be used under compression load are introduced. These DES contain special profiled elastomer surfaces which stretch the elastomer film under compression. Moreover, the electrode layers may be arranged in different positions leading to several distinct sensor designs. The elastomer film and the profiles were made from silicone rubber and the electrode layers contain carbon black particles embedded in silicone. Depending on the special design of the DES, the detectable capacitance change may reach more than 100 %. The sensitivity of the sensor is determined by the sensor design as well as the hardness of the silicone. These compressible sensor mats offer a high potential for a multitude of applications such as seat occupation surveillance or pressure distribution monitoring for medical purposes. Optionally, the sensor mat can also be equipped with electrode patterns, in order to measure the pressure distribution with local resolution. Several examples of novel compression sensors and their properties and applications are outlined in the paper.

9056-40a

Bi-stable dielectric elastomer actuator

Samuel Shian, Roger M. Diebold, David R. Clarke, Harvard Univ. (United States)

Dielectric elastomer actuators (DEA) can be used to convert electrical potential into mechanical force with relatively large displacement or high actuation strain. Such displacement, however, is inherently un-stable and the actuator will eventually return to the initial state once the electrical potential is removed or leaks away. To maintain an actuated state, a constant electrical potential must be provided and, consequently, the actuator consumes electrical energy. To overcome this limitation, we proposed a DEA configuration that utilizes the flow of fluid to create bi-stable or multi-stable actuation using a single active actuator. Such a single actuation mechanism simplifies the construction and eliminates the need for complex composite driving schemes. In this presentation, we will provide details of the construction and control mechanisms for our bi-stable actuator device. Preliminary experimental results indicate that the device is capable of maintaining an actuated state for a significant

times, of the order of hundreds of second, after the electrical potential is removed while maintaining sub-second actuation response time. We further demonstrate the utility of the bi-stable actuator in practical devices, such as actuators for refreshable Braille's display.

9056-41a

Optimized control algorithms for feeding DEAP: transducer with bidirectional power electronics

Jürgen Maas, Thorben Hoffstadt, Ostwestfalen-Lippe Univ. of Applied Sciences (Germany)

Transducers based on dielectric eletroactive polymers (DEAP) use the electrostatic pressure to convert electrical energy into mechanical energy or vice versa. Besides an intelligent setup of the transducer depending on the application, bidirectional high voltage power electronics with high efficiency are indispensable. Due to the capacitive behavior of the DEAP current controlled DC/DC converter are used to charge and discharge the DEAP.

In this contribution a bidirectional flyback-converter, which is suitable for small to average power outputs and has a comparable simple circuit design, and a bidirectional full bridge converter operated as dual active bridge for high power outputs but with a more complicated circuit design are investigated and compared in detail. Detailed models of both topologies are derived considering loss mechanisms like switching losses of the semiconductors and conduction losses. Based on these models the modulation schemes of the semiconductors are optimized in order to obtain either an energy optimal behavior by minimizing the losses, or a time optimal behavior offering the highest possible dynamics.

In order to drive DEAP transducers in a closed loop control for example in positioning applications or for energy harvesting the feeding voltage at the DEAP needs to be controlled. Therefore, high dynamic current-voltage controls for the both investigated converters under consideration of the optimized modulation schemes are designed.

For the evaluation of the efficiency and dynamics, simulation and experimental results of realized prototypes of both converter topologies will be presented under consideration of the developed control algorithms and modulation schemes.

9056-42a

Artificial muscles of dielectric elastomers attached to artificial tendons of functionalized carbon fibers

Zhihang Ye, Shahnewaz Sabit Faisal, Ramazan Asmatulu, Zheng Chen, Wichita State Univ. (United States)

Dielectric elastomers are soft actuation materials with promising applications in robotics and biomedical devices. Traditional dielectric elastomers are coated with two thin metal electrodes, such as gold and silver. The dielectric elastomer contracts when a DC electric voltage (higher than 100 V) is applied to the electrodes. However, when larger deformations are generated, the electrodes pier off due to the poor adhesion between the metal electrodes and elastomer, so some cracks are formed on the electrodes because of the weak strength of thin metal electrodes.

In this paper, a novel artificial muscle structure with dielectric elastomers (PDMS) and functionalized carbon fibers is presented. This structure consists of a dielectric elastomer as actuator and two bunches of carbon fibers as electrode and tendon. Carbon fibers are highly popular for their high electrical and thermal conductivities, mechanical strengths, and biocompatibilities. After the acid treatments for the functionalization of carbon fibers (500nm - 10µm), one end of carbon fibers was spread into dielectric PDMS elastomer, while the other end was connected to the DC power supply. After curing of elastomer with the carbon fibers, the tiny individual fibers tightly grasped the elastomer with the large surface contacting area, which provide strong adhesion between elastomer and electrodes.

Tension tests were conducted on the prepared artificial muscle system to investigate the adhesion between the elastomer and carbon fibers and stiffness of the hybrid structure. Actuation capability of the novel artificial muscle has been characterized by load cell and laser sensor. In the first investigation, a robotic arm was built with two artificial muscles which are in differential actuation configuration. Preliminary results were highly promising to use this system in the application of robotic assistive devices for the humanitarian purposes.

9056-43a

Elastic dielectric composites: a microscopic field theory and applications

Oscar Lopez-Pamies, Univ. of Illinois at Urbana-Champaign (United States)

In this talk, I will present a microscopic field theory that aims at describing, explaining, and predicting the macroscopic response of elastic dielectric composites with two-phase particulate (periodic or random) microstructures under arbitrarily large deformations and electric fields. The central idea rests on the construction --- via an iterated homogenization technique in finite electroelastostatics --- of a specific but yet fairly general class of particulate microstructures which allow to compute exactly the homogenized response of the resulting composite materials. The theory is applicable to any choice of elastic dielectric behaviors (with possibly even or odd electroelastic coupling) for the underlying matrix and particles, and any choice of the one- and two-point correlation functions describing the microstructure. In spite of accounting for fine microscopic information, the required calculations amount to solving tractable first-order nonlinear (Hamilton-Jacobi-type) partial differential equations.

As a first application of the theory, explicit results are worked out for the basic case of ideal elastic dielectrics filled with initially spherical particles that are distributed either isotropically or in chain-like formations and that are ideal elastic dielectrics themselves. The effects that the permittivity, stiffness, volume fraction, and spatial distribution of the particles have on the overall electrostrictive deformation (induced by the application of a uniaxial electric field) of the composite are discussed in detail.

9056-44b

EAP sensors for human body motion *(Invited Paper)*

Benjamin M. O'Brien, Todd A. Gisby, StretchSense (New Zealand) and The Univ. of Auckland (New Zealand); Iain A. Anderson, The Univ. of Auckland (New Zealand) and StretchSense (New Zealand)

Sensing motion of the human body is a difficult task. From an engineers' perspective people are soft highly mobile structures that move in and out of unstructured environments. As well as the technical challenge of sensing, concepts such as comfort, social intrusion, usability, and aesthetics are paramount in determining whether someone will adopt a sensing solution or not.

At the same time the demands for human body motion sensing are growing fast. Athletes want feedback on posture and technique, consumers need new ways to interact with augmented reality devices, and healthcare providers wish to track recovery of a patient.

Dielectric elastomer Electro-Active Polymer (EAP) stretch sensors are ideal for bridging this gap. They are soft, flexible, and precise. They are low power, lightweight, and can be easily mounted on the body or

embedded into clothing. From a commercialisation point of view stretch sensing is easier than actuation or generation – such sensors can be low voltage and integrated with conventional microelectronics.

This paper takes a birds-eye view of the use of these sensors to measure human body motion. The pros and cons of stretch sensors will be presented alongside a review of different motion capture technologies. The paper will finish with guidelines for EAP sensing and a speculation on the future direction and challenges of the technology.

9056-45b

Electromechanical sensing of ionic polymer metal composites

Youngsu Cha, Filippo Cellini, Maurizio Porfiri, Polytechnic Institute of New York Univ. (United States)

Ionic polymer metal composites (IPMCs) are an emerging class of soft electroactive materials that are recently finding application as sensors and energy harvesters. IPMCs are composed of a hydrated ionomeric membrane that is sandwiched between two noble metal electrodes. Several physical phenomena, such as ionomer swelling, counterion diffusion, and the formation of electric double layers, underpin the transduction of energy in IPMCs. However, a thorough understanding of the relative influence of such phenomena is yet to be clearly established. Here, we propose a physics-based modeling framework based on the Poisson-Nernst-Planck system to describe IPMC electromechanical response to an imposed time-varying flexural deformation. Specifically, we account for the swelling of the ionomer core and composite layers and the forced counterion convection associated with the IPMC motion. We utilize the method of matched asymptotic expansions to establish a closed-form solution for the electric potential and counterion concentration in the IPMC. Notably, the model predicts that the IPMC open-circuit voltage is independent of the time rate of deformation and linearly correlated to the mechanical curvature, with a coefficient of proportionality that is a function of the ionomer thickness and the thermal voltage. Thus, the model demonstrates that the characterization of IPMC electrical impedance suffices to identify all the parameters that are relevant to sensing, in contrast to the state of knowledge of black-box models that require ad-hoc experiments for calibration. Theoretical results are validated through experiments on in-house fabricated patterned IPMC samples that are subject to mechanical deformations.

9056-46b

Soft capacitive touchpad

Daniel Xu, The Univ. of Auckland (New Zealand); Benjamin M O'Brien, Todd A Gisby, StretchSense Ltd (New Zealand); Iain A. Anderson, The Univ. of Auckland (New Zealand)

The human mind is a vibrant fountain of ideas. Mixed in the turbulence is a creative imagination that is flooding with expressions and emotions. Our hands are a natural extension of this flow. Through our ability to draw, we are able to describe even complex ideas simply and precisely. Every different stroke possesses a particular meaning, where even the tiniest detail can change the understanding. By capturing the raw essence of this expression, we can interact with devices, computers and robots on a more intimate level than before, breaking away from the confinements of mechanical switches and digital logic.

Building on the latest developments of strain sensing for dielectric elastomers, a pressure sensitive interactive touchpad is described to sense touch in real time. The touchpad consists of 16 independent capacitive segments, allowing in-plane interaction and pressure perception. By utilizing the elastomer's intrinsic elasticity and softness, this device creates a more connected level of interactivity than traditional touchpads. The entire system is self-contained, portable and requires no external processors.

9056-47b

Identification of the mechanical state of DEAP transducers based on integrated DEAP sensors

Martin Griese, Thorben Hoffstadt, Jürgen Maas, Ostwestfalen-Lippe Univ. of Applied Sciences (Germany)

Dielectric electroactive polymers (DEAP) are thin films made of elastomeric material coated with compliant and conductive electrodes.

Besides the actuator and generator functionality, they are also predestined for sensor applications to monitor the actual mechanical state based on the deformation dependent electrical parameters of the DEAP. Considering DEAP actuators for positioning applications, like stack- or roll-actuators, the actual position, length or stretch of the actuator is required for the control. Thus, integrated sensors made of DEAP can be used to determine the actual stretch state precisely and with high dynamics. In order to ensure a high sensitivity and accuracy of the resulting stretch signal, a suitable sensor concept is required. These concepts can be distinguished between sensor-less and sensor-based concepts. While within sensor-less concepts the transducer itself is used, sensor-based concepts require additional sensor films integrated into the transducer.

Within this contribution an abstract of the proposed sensor concepts is presented, which are designed for stack- and roll-actuators with mechanical constraints like end caps. In order to evaluate the sensor-based concepts, an electromechanically coupled FEM simulation is used. Besides the mechanical boundary condition due to the end caps, the electrically dependent deformation is considered. In order to determine the stretch-dependent electrical parameters an appropriate identification algorithm is required, which considers all losses of a DEAP actuator. Regarding the frequency domain new algorithms are presented which have a high potential by usage in combination with the feeding power electronics. Additionally, these new algorithms are also evaluated by simulations and experimental measurements.

9056-48b

Highly sensitive proximity and tactile sensor based on composite with dielectric elastomer and carbon microcoils

Hyouk Ryeol Choi, Tien Dat Nguyen, Canh Toan Nguyen, DongHyuk Lee, Uikyum Kim, Choonghan Lee, Hoa Phung, Hyungpil Moon, Ja Choon Koo, Sungkyunkwan Univ. (Korea, Republic of)

In this work we present a new sensor for collecting proximity and tactile information by using a composite with dielectric elastomer (DE) and Carbon Microcoils (CMC). CMC is a coil-like carbon microstructure with several micro meter scale. The dielectric elastomer matrix mixed with CMC produces unique characteristics such as the change of impedance according to the change of distance with the object and physical contact. Especially, the impedance change of the DE matrix according to the distance can have the possibility to be used as a proximity sensor.

Basic mechanism of sensing is reported as the electrical resonance of the DE and CMC composite. We model the phenomenon as a total electrical circuit for bringing it into a practical use. Especially, how the sensing characteristics between the proximity and tactile sensing change are more intensively investigated, that is for dual use.

Using these characteristics of CMC based on NBR, we developed prototype of CMC tactile sensor system with highly sensitivity and the ability to measure a very small applied force. The prototype of the sensor consists of 4 x 4 sensing cells and its feasibility is demonstrated.

This sensor system can be well compared to other sensors and suited to use for artificial skin and the other applications.

9056-49a

The effect of converter efficiency on DEAP-based energy conversion: an overview and optimization method

Rick C. L. van Kessel, SBM Offshore (Monaco) and Technische Univ. Delft (Netherlands); Pavol Bauer, Jan Abraham Ferreira, Technische Univ. Delft (Netherlands); Ambroise Wattez, SBM Offshore (Monaco)

This work aims to close the gap between the Dielectric Electro Active Polymers (DEAP) transduction principles on the one hand, and the power electronic aspects on the other hand. For typical industrial applications having low strain levels, e.g. less than 60%, it is shown that the losses in the Power Electronic Converter (PEC) due to the cyclic charging and discharging of the DEAP are dominant in the conversion process.

The power electronic challenges that are specific to DEAP energy conversion, such as wide converter operating ranges, high peak-to-average ratios and subsequent low DEAP conversion efficiencies, are stressed. The effect of small strain cycles is discussed and novel charging and discharging current waveforms are proposed and investigated.

The voltage and current dependent efficiency profile of a realistic, high-voltage modular PEC was measured and taken as an input to an optimization algorithm. The current amplitude, phase and shape are optimized, and different cycle types are compared. The optimization has been performed for a wide range of strain levels, resulting in customized harvesting cycles for each operating point.

It is demonstrated that with properly adapted harvesting cycles, DEAP energy harvesting is feasible with very low strain levels down to 5%. As opposed to what is generally understood, it is found that constant-charge cycles are most efficient in small strain cycles. It is also shown that with respect to start of the art, non-optimized systems, significant efficiency gains up to 50% are achievable for both high and low strain cycles.

9056-50a

DEAP-based energy harvesting using vortex induced vibrations

Thorben Hoffstadt, Ostwestfalen-Lippe Univ. of Applied Sciences (Germany); Robert Heinze, Tim Wahl, Frank Kameier, Fachhochschule Düsseldorf (Germany); Jürgen Maas, Ostwestfalen-Lippe Univ. of Applied Sciences (Germany)

Besides the actuator functionality, dielectric electroactive polymers (DEAP) can also be used in the inverse operation mode as generators. While fundamental energy harvesting cycles have already been investigated in detail, appropriate generator setups have to be developed to convert ambient energy into electrical energy.

Based on considerations of vortex induced vibrations, a dielectric elastomer generator (DEG) setup is developed consisting of a circular cylinder and several DEAP elements. With the DEG, flow energy can be converted into electrical energy, if the flow, e.g. a water current, induces oscillations of an elastically mounted circular cylinder. In a certain range of the flow velocity this effect is called lock-in and the oscillation is used to excite the DEG. While the lock-in effect has been demonstrated using classical linear springs, within this study the use of DEAP-material with strongly non-linear material behavior is experimentally and numerically investigated.

Besides the validation of the general DEG setup further investigations concerning the control of the energy harvesting cycles are carried out. Due to the electromechanical interaction of DEAP the mechanical behavior of the DEG is affected by its electrical state. On the one hand this results in a system that can be adapted to the actual flow conditions. On the other hand a part of the ambient energy is converted into electrical energy, whereas only a certain amount of energy should be converted in order to sustain the oscillation. Thus, an intelligent harvester control is necessary.

9056-51a

Loading system and control electronics for equi-biaxial dielectric elastomer generator

Claudio Luzzio, Marco Fontana, Rocco Vertechy, Scuola Superiore Sant'Anna (Italy)

Dielectric Elastomers are non-conducting, highly deformable solids that experience large finite deformations in response to applied electric fields and that alter the existing electrostatic fields in response to the deformations undergone. DEs have shown very promising performances suitable for the development of energy harvesting devices based on the variable-capacitance electrostatic generator principle.

Several types of DEG have been implemented according to different deformation states that are imposed to DE membranes including uniform or non-uniform and uni- or multi-axial stretch. The equi-biaxial stretching is the most efficient state of deformation that can be employed in order to maximize the amount of energy that can be extracted in a cycle by a unit volume of DE.

In previous works, experimental tests of have been conducted using specimens of acrylic elastomers (VHB 4905, by 3M®) undergoing to equi-biaxial deformation. A maximum experimentally measured energy density of 560 J/kg have been achieved but for limited number of repetition of harvesting cycles. Such limitation is mainly attributed to the high viscoelasticity of the employed material.

This paper presents a novel mechanical loading system for inducing equi-biaxial state of deformation that can employ different types of materials including natural rubbers and silicone elastomers. Energy harvesting cycles are implemented via a custom electronic prototype that maximizes performances close to theoretical limits. Experimental results are presented which show and compare the performances of different materials.

9056-52a

Hardware in the loop simulation of dielectric elastomer generator for wave energy harvesting

Gastone Pietro Rosati Papini, Marco Fontana, Rocco Vertechy, Scuola Superiore Sant'Anna (Italy)

Dielectric Elastomers (DEs) are a very promising technology for the development of energy harvesting devices based on the variable-capacitance electrostatic generator principle. As compared to other technologies, DE Generators (DEGs) are solid-state energy conversion systems which potentially feature: 1) large energy densities; 2) good energy conversion efficiency that is rather independent of cycle frequency; 3) easiness of manufacturing and assembling; 4) high shock resistance; 5) silent operation; 6) low cost.

One of the most promising fields of application for DEGs is in the ocean energy sector, where they could be used to replace traditional Power Take Off (PTO) systems of Wave Energy Converters (WECs) that are based on conventional hydraulic and electromagnetic machinery.

To date, the performances of DEGs have mostly been studied in ideal conditions by coupling them to an external mechanical source with infinite impedance (namely a displacement generator with no force saturation). However, in realistic applications, the practical energy that can be converted by a DEG significantly depends on the inertia, damping and springy properties of the external source.

In this context, the paper investigates the experimental performance of a DEG PTO via a properly predisposed Hardware-In-the-Loop

(HIL) simulation test-bench of a practical WEC, in realistic sea wave conditions. The HIL system is coupled to the considered DEG PTO via sensors and actuators, and is employed as an external energy source with variable impedance mimicking that of WEC-wave hydrodynamics.

9056-53a

Energy scavenging strain absorber: application to kinetic dielectric elastomer generator

Claire Jean-Mistral, Maxime Beaune, Institut National des Sciences Appliquées de Lyon (France); Thanh Vu-Cong, Alain Sylvestre, G2Elab (France)

Dielectric elastomer generator (DEG) are light, compliant, silent energy scavengers. They can easily be incorporated into clothing where they could scavenge energy from the human kinetic movements for biomedical applications. Nevertheless, scavengers based on dielectric elastomers are soft electrostatic generators requiring a high voltage source to polarize them and high external strain, which constitutes the two major disadvantages of these transducers. We propose here a complete structure compiosed of a strain absorber, a DEG and a simple electronic power circuit. This new structure looks like a patch, can be attached on human's wear and located on the chest, knee, elbow… Our original strain absorber, inspired from a sailing boat winch, is able to heighten the external available strain with a minimal factor of 2. The DEG in silicone Danfoss Polypower, has a total area of 10cm per 5cm sustaining a maximal strain of 20% at 1Hz. A complete electromechanical analytical model was developed for the DEG associated to this strain absorber. A power of 125µW at 1Hz is expected with a bias voltage of 750V, enough to supply a low consumption system. Mechanical experimental validation was realized on the strain absorber underlying specific losses, decreasing with the increasing of the multiplication factor. With an external imposed strain of 10%, a scavenged energy of 37µJ per cycle is achieved with our complete structure. The performance of the DEG can further be improved by enhancing the imposed strain, by designing a stack structure, by using a dielectric elastomer with high dielectric permittivity.

9056-54b

Beyond artificial muscle: bio-inspired transformative skin and microlens based on dielectric elastomers *(Invited Paper)*

Xuanhe Zhao, Duke Univ. (United States)

Subject to a voltage, a layer of a dielectric elastomer reduces in thickness and expands in area, giving actuation stress and strain similar to those of human muscles. Over the last decade, dielectric elastomers have been intensively investigated as candidates for artificial muscles.
In this talk, we will present novel non-conventional applications of dielectric elastomers as transformative skin and microlens. The working mechanism for the new applications is based on new modes of voltage-induced deformation and instability in dielectric elastomers recently discovered in our group. Subject to an electric voltage, a substrate-bonded polymer film initially maintains flat and smooth. Once the voltage reaches a critical value, regions of the polymer surface locally fold against themselves, giving a variety of patterns including creases, craters and lines. The dynamic interactions of the patterns with environment can lead to novel applications as transformative skins for antifouling, transfer printing and camouflage. In addition, electric voltages can deform micro-droplets encapsulated in dielectric elastomers into ellipsoidal and tube shapes, giving the electrocavitation instability. The deformation and instability can be used to tune the micro-droplets as microlenses for various applications. Inspirations from biological systems are particularly helpful in designing the transformative skin and microlens, and will be shared with the audience.

9056-55b

Challenges of using dielectric elastomer actuators for eye-like-focus tunable lens

Lau-Gih Keong, Thanh-Giang La, Li-Lynn Shiau, Adrian W. Y. Tan, Nanyang Technological Univ. (Singapore)

Recently, dielectric elastomer actuators (DEAs) have been adopted to tune liquid membrane lens, just like ciliary muscles do to the lens in human eye, which offer advantages of stable shape, long lifetime, and large focus range (7cm to infinity). However, DEA tune lens faces some challenges, such as high stress, membrane puncture, high driving voltage requirement, and focus distance not more than 707cm, that limit its practical use. The design problem gets more complex as the liquid lens shares the same elastomeric membrane as the DEA. To address these challenges, we separate DEA from the lens membrane. Instead, a liquid-immersed DEA, which is safe from terminal failure, is used as a diaphragm pump to inflate or deflate the liquid lens by hydraulic pressure amplification. When activated, a membrane DEA (VHB 4905), which is immersed in oil between two hydraulic chamber, bulges from one hydraulic chamber towards another to build up internal pressure that change the membrane curvature of the liquid lens. Hydraulic amplification can be achieved by designing a pump chamber with a larger volume than that of the lens enclosure. In this way, it could induce a large curvature change in the liquid-membrane lens. In addition, the DEA can be thinned down and stacked up, independent of the lens membrane thickness. Preliminary study showed that our 8-mm-diameter tunable lens can focus objects in the range of 15cm to 50cm with a small driving voltage of 1.8kV. Future work will further improve hydraulic chamber design to achieve far focusing (towards infinity), and reduce the driving voltage (less than 1kV) by thinning and stacking DEAs membranes. Hopeful, such DEA tune lens can find suitable applications to miniaturized camera in endoscopy system and mobile phone.

9056-56b

Transparency-switching shape memory gels

Jin Gong, Masanori Arai, Shota Murata, Md. Hasnat Kabir, Masato Makino, Hidemitsu Furukawa, Yamagata Univ. (Japan)

Shape memory (SM) materials are a class of intelligent materials that have the ability to "memorize" a macroscopic (permanent) shape. Gels have the closest properties to the tissues of life. Therefore, SM gels have aroused great attention due to their capacity to remember two shapes at different conditions and the property close to life materials. This gives SM gels great potential for application in biomedical, sensors, actuators, and other smart device fields.

Crystalline short side chains, cross-linked long main chains and the liquid medium of water together play a fundamental role inside SM gels when relating the microstructure with its macroscopic nature. SM gels can be fixed at a temporary shape below their transition temperature (Ttrans≈50?), because the side chains take order structure like crystals (crystallization). During the programming process, the entropy elasticity is stored in cross-linked long main chains. This is the recovery force that SM gels are forced back to their permanent shapes. The process of deforming the SM gels and fixing their intended temporary shapes is called programming, which either consisting of heating up the sample, deforming and cooling the sample. Heating up the SM gels to around 50? induces the shape-memory effect. The permanent shapes of SM gels are recovered as soon as the switching temperature Ttrans reaching to around 50?. The ON/OFF switching of transparency at Ttrans aslo is found for our SM gels. The switching temperature Ttrans can be adjusted freely in the range of 0?60? by changing the chemical compositions of SM gels.

9056-57b

Optical functionality of natural photonic structures on the transparent insect wings for bio-mimetic applications

Pramod Kumar, Indian Institute of Science Education and Research (India)

Nature has developed a broad range of gorgeous hierarchically organized architecture in the insect wings for multifunctional purpose. Particularly, the transparent wings seem to have a simple structural design but hide a largely unexplored complex spatial organization of several micron-sized elements arranged on the length scale comparable to their size [1]. Hence, an understanding of the symmetry in natural structural arrangements is crucial in exploring novel optical effects for biomemetics photonic structures as well as functional significance of their design. Numerous studies have sought to discover and characterise the photonics associated with a diverse range of natural system. However light behaves within these structures has not been well understood until now. The aim of this paper is thus to address the following questions: How the transparent wing-system is assembled in local and global length scale from nanometre to micrometer? Can the optical method unveil new features in the wing architecture?

We experimentally and numerically probe the natural quasi-ordered complex structures in the transparent insect wings by a simple, non-invasive, real time optical diffraction technique using monochromatic lasers and broadband femtosecond laser pulses [2, 3]. A complex diffraction pattern in transmission unveils the signature of long range spatial correlation in structural arrangement (symmetry) at various length scales on the whole wing surface for a variety of insect wings. A qualitative analysis of the fast Fourier transform (FFT) angular spectrum reveals a direct link between the structural organization and optical transmitted diffraction patterns. Our findings directly demonstrate how the diffraction pattern through the transparent insect wings is spatially and functionally correlated with its structural origination at various length scales. The methodology of the studies developed in this paper is applicable to a wide class of disordered photonic crystal structures.

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9056-58a

Dielectric elastomer cantilever beam sensor

Na Ni, Ling Zhang, Jinxiong Zhou, Yin Wang, Fan Liu, Xi'an Jiaotong Univ. (China)

Delectric elastomer sensors are a recent type of mechanical sensors which can be used to detect forces, pressures and deformations. The sensors have several advantages compared with traditional sensors including high elasticity, capacitive sensing and inexpensive fabrication. In this paper, a new sensing device for measuring small concentrated force is proposed. This device deploys the dielectric membrane on the surface of cantilever beam of constant strength. The dielectric membrane is a capacitance sensor built with dielectric polymer coated with soft electrodes. The change in strain arising from cantilever beam with concentrated force at free end can be quickly transferred to the dielectric membrane. The strain variation of the dielectric membrane induce the change in the capacitance of the membrane. Tests on the device show that the concentrated force at the free end of cantilever beam is nearly proportional to the change in the capacitance. According to this relationship, the unknown concentrated force can be obtained accurately by measuring the change in the capacitance of the dielectric membrane. The new device is capable of monitoring small concentrated force with prominent sensitivity and response times.

9056-59a

Parallel input parallel output high voltage bi-directional converters for driving dielectric electro active polymer actuators

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Dielectric Electroactive polymer (DEAP) actuators are capacitive devices providing mechanical motions when charged electrically. The charging characteristics are dependent on actuators size, voltage applied and the required frequency. While the focus has been given to establish the electromechanical characteristics and application-based designs of actuators, little is done in developing the necessary electrical drivers. Commercially available laboratory equipment e.g. high voltage (HV) amplifiers are often used to operate such actuators. Although such amplifiers provide the necessary signals for lab experiments, they are inadequate in real applications as they are bulky and expensive. Therefore, electrical drivers specifically designed to both operate the actuators while being compatible with applications is needed. Scalability of such drivers is of outmost importance for their use in various applications with different operational requirements.

This paper presents the design and implementation of parallel input parallel output (PIPO) bi-directional high voltage (~2500 V) DC-DC converters specifically designed for DEAP actuators. The topology is a bi-directional flyback converter incorporating commercially available HV MOSFETS (4 kV) and diodes (5 kV). Although the electrical current of the aforementioned parts is limited to <150mA, connecting multiple units in parallel still provide a scalable design. This enables operating DEAP actuators in various static and dynamic applications e.g. positioning, vibration generation or damping, and pumps. The proposed concept is experimentally verified with two units connected in parallel, to operate one DEAP actuator. The paper also investigates using more units to find a potential optimum number of which should be used for one single DEAP actuator.

9056-60a

Aluminum nanoparticle/acrylate copolymer nanocomposites for dielectric elastomers with high dielectric constants

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Dielectric elastomers are useful for large-strain actuation and energy harvesting. Their application has been limited by their low dielectric constants and consequently high driving voltage. Various fillers with high dielectric constants have been incorporated into different elastomer systems to improve the actuation strain, force output and energy density of the compliant actuators and generators. However, agglomeration may happen in these nanocomposites, resulting in a decrease of dielectric strength, an increase of leakage current, and in many instances the degree of enhancement of the dielectric constant. In this work, we investigated aluminum nanoparticles as a suitable nanofiller for an acrylate copolymer. This metallic nanoparticle was chosen because the availability of free electrons could potentially provide an infinite value of dielectric constant as opposed to dielectric materials including

ferroelectric nanocrystals. Moreover, aluminum nanoparticles have a self-passivated oxide shell effectively preventing the formation of conductive path. The surfaces of aluminum nanoparticles were functionalized with methacrylate groups to assist the uniform dispersion in organic solutions and additionally enable copolymerization with acrylate copolymer matrix during bulk polymerization, and thus suppresses large range drifting of the nanoparticles. The resulting Al nanoparticle-acrylate copolymer nanocomposites were found to exhibit higher dielectric constant and increasing stiffness. The leakage current under high electric fields were significantly lower than nanocomposites synthesized without proper nanoparticle surface modification. The dielectric strengths of the composites were comparable with the pristine polymers. In dielectric actuation evaluation, the actuation force output and energy specific work density were enhanced in the nanocomposites compared to the pristine copolymer.

9056-61a

How does static stretching decreases the dielectric constant of VHB 4910 elastomer?

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Subject to a voltage, dielectric elastomers can deform by the effect of the Maxwell stress which directly depends on the dielectric constant of the material. The association of large strain, soft elastic response and good dielectric properties established that VHB 4910 elastomer constituted one of most interesting materials for dielectric elastomer actuators. However, the effect of a stretch on the dielectric constant of this elastomer is discussed and subjected to controversy in the literature. Indeed, the dielectric constant of this material decreases slightly or hugely following the stretching but any pertinent physical explanation to translate this behavior is satisfactory at this time. In this paper, we will present a fully study about the dielectric behavior of VHB 4910 elastomer versus a broadband of stretching and for various temperatures. Among all the explanations of the stretch dependence of dielectric constant of VHB 4910 in the literature, the crystallization, the change of the glass transition temperature, the decrease of the dipole orientation and the electrostriction effect under stress were proposed, from our results, we conclude that the decrease of the dipole orientation appears as the more probable and the main reason explaining the decrease of the dielectric constant of this elastomer versus the stretching. An accurate law is proposed to represent the changes observed in the dielectric constant according to the stretch and the temperature. Then, this law can be further used for a better prediction of performances for dielectric elastomer actuators based on VHB 4910.

9056-62a

Periodic compression of small cell cultures: harnessing stress in passive regions of dielectric elastomer actuators

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We present a dielectric elastomer actuator (DEA) for in vitro analysis of square millimeters biological samples under compressive stress. Understanding how mechanical stimuli affect cells functions could lead to significant advances in diseases diagnosis and drugs development. We previously reported an array of micro DEAs for cell stretching which overcomes the throughput limitation of traditional micro scale approaches.

To diversify our cell biomechanics and mechanotransduction toolkit we have developed an actuator for periodic compression of cell populations. The device is based on a novel design which exploits effects of non-equibiaxial prestretch and stress induced by DEAs in passive regions of a silicone membrane. Two uniaxial actuators are aligned along their deformation direction and separated by a 2mm x 2mm passive area. When driven with an alternative voltage source the two DEAs periodically compress this passive area by more than 10%. The electrodes configuration confines the electric field and prevents it from reaching the biological sample. A 5 microns thick layer of silicone is casted on top of the device to ensure a biocompatible environment. This design provides several advantages over alternative technologies such as high optical transparency of the area of interest (passive region under compression) and its potential for miniaturization and parallelization.

This contribution will detail the actuator novel design and working principle. The optimization parameters will also be presented and discussed, showing how stress in DEAs passive areas can be harnessed to achieve compressive stress of relevant amplitude.

9056-63a

Model-based optimization of DEAP-roll-actuators with a polymer core

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Dielectric electroactive polymers (DEAP) are thin films made of elastomeric material coated with compliant and conductive electrodes. Since they offer a large amount of deformation these materials have a high potential for actuator- and also generator-applications.

By winding up a biaxially pre-stretched DEAP-material around a compressed polymer core a roll-actuator can be realized, which elongates axially, if the DEAP's capacitance is charged electrically. Within this actuator design the compression of the polymer core is used to preserve the pre-stretch of the DEAP-material.

Based on the analytical model of this roll-actuator, describing the hyperelastic material behavior of the DEAP and the polymer core as well as the electrical behavior of the DEAP, the overall behavior of this actuator is optimized. This behavior of the polymer core roll-actuator is characterized by the blocking force, the no load strain and the mechanical energy stored in the actuator. Therefore, in a first step equations to determine these characteristic quantities are derived from the analytical model. Based on these equations the influences of different material parameters as well as design parameters, e.g. the geometry or the pre-stretch ratios, are discussed. This yields to the determination of optimized design parameters to maximize the mentioned characteristic quantities, so that design rules for optimized actuators can be stated.

Finally, actuators with optimized design parameters are fabricated and measured to validate the stretch-force behavior of the optimized polymer core roll-actuators.

9056-64a

Open-access dielectric elastomer property database

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Dielectric Elastomers (DEs) are a particular class of multi-functional polymers. DEs are non-conducting, highly deformable and nearly incompressible rubber-like solids that experience large finite deformations in response to applied electric fields and that alter the existing electrostatic fields in response to the deformations undergone.

Exemplary DE materials are: silicone elastomers, natural rubber, acrylic elastomers, polyurethanes and styrene-butadiene rubber (both in unfilled and filled form).

Thanks to the strong electro-mechanical coupling, DEs intrinsically offer great potentialities for conceiving novel solid-state mechatronic transducers (such as actuators, sensors and generators) which are more integrated, lightweight, economic, silent, resilient and disposable than equivalent devices based on traditional materials and technologies.

The development of effective DE transducers requires the accurate knowledge of the non-linear constitutive behavior of the considered materials. In this context, the paper presents an open-access electro-mechanical property database for DEs that has been specifically developed to support the practicing engineer in the design and optimization process. For each material response (that includes hypereslaticity, dielectric susceptibility, dielectric strength and current leakage), the paper describes constitutive models and experimental measurement procedures.

In order to give some example, constitutive parameters and ultimate field values are reported for three commercial DE materials (a silicone elastomer, an acrylic elastomer and a natural rubber).

9056-65b

On the geometrical and mechanical multi-aspect optimization of PPy/MWCNT actuators

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Polypyrrole (PPy) conducting polymers as one of the most well-known actuation materials have shown numerous applications in a variety of fields such as biomedical devices as well as biomimetic robotics. This study investigates the multiobjective optimization of a PPy/MWCNTs actuator through an electrochemomechanical model. The multilayer actuator is composed of a PVDF layer, as the core membrane and an electrolyte reservoir, as well as two nanocomposite films deposited on each side of the PVDF layer. The nanocomposite film comprises electropolymerized pyrrole along with multiwalled carbon nanotubes. In addition, the electropolymerization process takes place in an electrolyte consisting of multiwalled carbon nanotubes dispersed in pyrrole. In order to obtain the optimum values for each decision variable (i.e., geometrical and electrochemical), the two main outputs of the bending actuator, the tip displacement and blocking force, have been mathematically modeled and formulated as the objective functions. A multiobjective optimization algorithm is applied to maximize the blocking force and tip displacement generated by the actuator. Furthermore, a range for each design variable is defined within which none of the objective functions of the film-type actuator dominates the other one while they are both kept within an acceptable range. The results obtained from the mathematical model are experimentally verified. Moreover, in order to determine the performance of the fabricated actuator, its outputs are compared with their counterparts of a neat PPy actuator.

9056-66b

Non-linear time variant model of PPy-based actuator

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Polypyrrole-based actuators are of interest due to their biocompatibility, low operation voltage and relatively high strain and force. Modeling and simulation are very important to predict the behavior of each actuator. To derive the correct and accurate model, we need to know the electro-chemo-mechanical specifications of the PPy. In this paper the non-linear time-variant model of PPy film is derived and proposed by combination of RC transmission line model and state space representation. Also, We have shown that the Ionic conductivity of PPy is not constant during the actuation and it is a function of applied voltage. The function of Ionic conductivity of PPy vs. Applied voltage has been proposed, implemented in non-linear model and validated by experiment. The Ionic conductivity of PPy decreases significantly in negative voltage region and it results reducing the current in Cyclic Voltammetry (CV) test. Contemplating the CV tests for different solutions with different ions, verifies this non-linear variation of Ionic conductivity vs. applied voltage. Results show the perfect consistency between model and experiment.

9056-67b

Robust control of a trilayer conducting polymer actuator

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Performance of the conducting polymer actuators (CPAs) are affected by material uncertainties, operating conditions and time of operation. The same size CPAs may have different actuation capabilities, which can also degrade over the course of operation. When these actuators are used for accurate and repeatable position tracking, the uncertainties and variations in the actuator dynamics have to be carefully addressed to achieve a desirable control performance.

This paper presents a systematic approach for the identification of sources of uncertainties and designing robust H_∞ control to achieve a guaranteed performance over the course of operation when the CPA is used for position tracking. We identify the sources of uncertainties in actuator dynamics by performing series of experiments using two different CPAs with the same size. A set of system models is obtained to determine the average actuation capability. The variations in the actuator dynamics are modeled as a parametric uncertainty, and the ignored dynamics is modeled as an additive uncertainty. An H_∞ controller is designed and its robustness in the presence of uncertainties and disturbances is validated by experiments. In the closed-loop control experiments, we use a different batch production CPA with the same size and apply an external force on the actuator tip. The performance of the H_∞ controller is also compared with a proportional-integral-derivative (PID) controller. We demonstrate that the robust H_∞ control strategy outperforms the PID controller in terms of speed of response, maximum overshoot and steady-state error and satisfies the control performance specifications.

9056-68b

Carbon-derived carbon (CDC) linear actuator properties in combination with conducting polymers

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Carbide–derived Carbon (CDC) material is applied for super capacitors due to their nanoporous structure [1] and their high charging/discharging capability. In recent years CDC material been applied for actuators [2, 3] (volume change, bending type) but the actuation displacement and speed found low in comparison to other carbon related material such as carbon nanotubes. To obtain CDC actuators the brittle carbon material is hot pressed with PVdF and ionic liquids [2] to obtain CDC polymeric linear actuators. In this work we report for the first time CDC and CDC combined with conducting polymers in ECMD (Electrochemomechanical deformation) under isotonic (constant force) measurements. CDC actuators combined with polypyrrole doped with DBS showing nearly double strain under cyclic voltammetric and square wave potential measurements in comparison to CDC linear actuators. The new material is investigated by SEM images, EDX and scanning ionic conductance microscopy (SICM) to investigate how the conducting polymer layer and the CDC layer interfere together.

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[2] J. Torop, V. Palmre, M. Arulepp, T. Sugino, K. Asaka, A. Aabloo, Flexible supercapacitor-like actuator with carbide-derived carbon electrodes, Carbon 49 (2011) 3113-3119

[3] J. Torop, T. Sugino, K. Asaka, A. Jänes, E. Lust, A. Aabloo, Nanoporous carbide-derived carbon based actuators modified with gold foil: Prospect for fast response and low voltage applications, Sensors and Actuators B 161 (2012) 629– 634

9056-69b

Development, analysis, and comparison of electromechanical properties of Buckypaper IPMC actuator

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With smart materials and adaptive structures being nudged into mainstream technology progressively, the smart composites are donning a predominant role as indispensable structures. Among these, the Ionic Polymer Metal Composites (IPMC), with their large bending deformation and relaxation characteristics at very low voltages and act as transducers with their actuation and sensing properties, have been sought after for various engineering applications. The paper focuses on combining the ionic polymer with Buckypaper electrodes to create a more enhanced IPMC, and comparatively analyzes the methodology with previous existing methodologies to prove the efficiency of this new method. The Nafion membrane is capable of ionic diffusion and this allows the formation of a solid electrolyte layer. The membrane and an ionic solution within the electrolyte cause the mobile ions contained within to sway to a particular direction when subjected to an electrical charge. This paper also concentrates on making use of different ionic solutions for comparison such as to determine the most effective ionic solution for the IPMC. This new functionally graded material is tested for its bending deformation and compared with conventional IPMCs and other Ionic IPMCs. By studying the electromechanical properties of this smart composite actuators based on their actuations under different electric excitations, we can draw conclusions subsequently from the results of the comparison.

9056-70b

Buckling of an ionic polymer metal composite shell under uniaxial compression

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Ionic polymer metal composites (IPMCs) are a novel class of soft electroactive materials that are composed of an ionomeric membrane sandwiched between two noble metal electrodes. Several implementations of IPMCs in mechanical sensing have been proposed in the last few years, whereby it has been shown that an imposed mechanical deformation results in a polymer swelling, which, in turn, generates a charge imbalance in the membrane. Such imbalance is ultimately responsible for a measurable voltage across the IPMC electrodes.

Here, we analyze mechanical sensing in IPMC shells that are loaded in uniaxial compression until buckling. A novel methodology to fabricate shell-like IPMCs is developed, which combines hot forming of soft polymers and electroless chemical reduction processes. A series of experiments is conducted to estimate the buckling load of the IPMC shell and to investigate the feasibility of detecting the onset of buckling from the short-circuit current. Experiments are performed on cylindrical shells with clamped-clamped boundary conditions under uniaxial compression. We estimate the Young's modulus of the samples using the load-displacement curves prior to the onset of buckling. High speed imaging is leveraged to investigate the samples' deformation and to characterize the buckling patterns. Moreover, the acquired images are utilized to synchronize the IPMC displacement with the short-circuit current to assess the possibility of detecting buckling through sharp variations in the IPMC current. Experimental findings on the critical load are interpreted through classical results on the buckling of thin shells and ad-hoc finite element simulations.

9056-71b

Force control of ionic polymer-metal composite actuators with carbon-based electrodes

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In order to perform tasks such as hold an object with a constant force, reliable control of an ionic electroactive polymer actuator is essential. The composite under research is an IPMC actuator with electrodes composed of nanoporous carbon and membrane made of ionic polymer. Compared to traditional platinum electrodes, these novel electrodes do not crack in clusters and have highly controllable properties which preserve even when the actuator is deformed. Thus far, there are no reports on the dynamic force response of this composite. We present the first attempts of testing the force dynamics of an IPMC with nanoporous carbon electrodes under both open- and closed-loop controls. Because many attempts have been focused on the sensorless force control of ionic electroactive polymers, we first investigated the uncompensated dynamics of the actuator and then used the direct inverse model to obtain the desired tracking performance. We also aimed to identify under which conditions the actuator is suitable for sensorless position control. Furthermore, we improved the tracking ability of the actuator using a feedback controller where the force sensor data is available and incorporated a feedforward controller into the feedback control system.

9056-72a

Stretchable, transparent, ionic conductors: sound from a transparent, soft membrane *(Invited Paper)*

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When electrical conductors are required to be compliant or transparent the properties of metals impede their use. Current research is focused on various types of electronic conductors. The presented work explores the use of ionic conductors in form of highly stretchable, ultra transparent films of hydrogel swollen with electrolyte in circuits that carry large voltages and operate at high frequencies - without electrochemical reactions. Experiments demonstrate hydrogels as electrodes for transparent, large strain (> 100%), high voltage powered dielectric elastomer actuators. High speed actuation is observed optically (> 1 kHz) and further presented in form of a fully transparent loudspeaker with frequency response up to 20 kHz. Unique measurement results (~ 99.99% transmittance at 550 nm, > 500% linear strain, sheet resistance < 200 ?/sq with weak dependence on strain) suggest the exploration of stretchable, transparent, ionic conductors as a new family of stretchable and transparent electrodes that may outperform ITO, graphene, carbon nanotubes and silver nanowires in compatible applications.

9056-73a

Colour gamuts in polychromatic dielectric elastomer artificial chromatophores

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Chromatophores are the colour changing organelles in the skin of animals including fish and cephelapods. The ability of cephalopods in particular to rapidly change their colouration in response to environmental changes, for example to camouflage against a new background, and in social situations, for example to attract a mate or repel a rival, is extremely attractive for engineering, medical, active clothing and biomimetic robotic applications. The rapid response of these chromatophores is possible by the direct coupling of fast acting muscle and pigmented saccules. In artificial chromotophores we are able to mimic this structure using electroactive polymer artificial muscles. In contrast to prior research which has demonstrated monochromatic artificial chromatophores, here we consider a novel multi-colour, multi-layer, artificial chromatophore structure inspired by the complex dermal chormatophore unit in nature and which exploits dielectric elastomer artificial muscles as the electroactive actuation mechanism. We investigate the mechanical and optical properties of this chromatophore unit and explore the range of colours and effects that a single unit and a matrix of chomatophores can produce. We demonstrate the colour gamut of the multi-colour chromatophore and show its suitability for practical display and camouflage applications. We show how, by varying actuator strain, chromatophore base colour and chromatophore geometry, the gamut can be shifted through colour space, thereby tuning the artificial chromatophore to a specific environment or application.

9056-74a

A new bistable electroactive polymer for prolonged cycle lifetime of refreshable braille displays

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The development of refreshable Braille displays has been hindered by the lack of a suitable actuator material capable of generating large out of plane deformation, precision pattern of multiple diaphragm dots, and large force support. Bistable electroactive polymers (BSEP) amalgamating the properties of electrically induced large-strain actuation and shape memory effects present a unique opportunity to fabricate refreshable Braille displays. The modulus of the BSEP film decreases by three orders or more from a rigid plastic state to a rubber state when heated above the polymer's glass transition temperature. The rubbery polymer film can be electrically actuated to buckle convexly when a high voltage is applied across a circular active area with 1.3 mm in diameter. By controlling the amount of long-chain crosslinker and monomers, which are essential to the transition temperature and elasticity of the film at rubbery state, the BSEP material was formulated to achieve enhanced stability of actuation. At raised dot heights of 0.4 mm, the actuation can be repeated for over 2000 cycles. The raised dot shape can be fixed by cooling the polymer below glass transition temperature. This rigid-to-rigid actuation simultaneously provides large-strain actuation and large force output, and is thus suitable for refreshable Brailled displays. Devices capable of displaying Braille characters over a smartphone screen area consisting of 40 Braille cells have been fabricated.

9056-75a

Bio-inspired autonomous crawling robot with an ionic EAP actuator

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The biomimetic robot prototypes based on ionic electromechanically active polymer (iEAP) actuators presented previously share as a rule one common feature – the electric power is supplied to these devices from an external supply through trailing wires. We present a crawling robot with a locomotion inspired by an inchworm. The robot includes a single iEAP actuator and an on-board lithium battery with a microprocessor for control purposes. The robot is able to move autonomously in ambient air conditions on a smooth surface. Stable operation in air is achieved by the use of non-volatile ionic liquid as an electrolyte.

The current attempt to create an autonomous robot gives a realistic evaluation for the applicability of state-of-the-art iEAPs in robotics, which is often considered as a perspective field of use for these materials. The results clearly demonstrate the advantages of iEAP actuators in robots in small (<10 mm) size scale, which is below the one comfortably achievable using conventional electromagnetic induction-based actuators. Power consumption and efficiency of an electromechanical system with iEAP actuators is discussed. The weight, size and power consumption of state-of-the-art semiconductor electronics is appropriate for such application; however, the optimization of energy storage is a major engineering issue.

In the constructed robot, the unique properties of iEAP technology – very large deflection amplitudes, low stiffness and low weight – are taken advantage of. A soft and flexible iEAP actuator is used also as a structural element, which is a common approach in bio-inspired morphing devices.

9056-76a

Carbon nanotube biscrolled yarn supercapacitors for microdevices

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Supercapacitor electrodes having engineered hierarchical structures on nano- and microscales can provide high energy and power densities as a result of large surface-to-volume ratios, appropriately inter-connected porosity, and exploitation of both non-Faradaic and Faradaic charge storage processes as power sources for miniaturized electronic devices electronic textiles, and implantable medical devices. We fabricate and characterize weavable, sewable, knottable and braidable yarns that function as high performance electrodes of redox supercapacitors. A novel technology, gradient biscrolling, provides fast-ion-transport yarn in which hundreds of layers of conducting-polymer-infiltrated carbon nanotube sheet are scrolled into ?20 μm diameter yarn. The exceptionally high energy and power densities for the complete supercapacitor, and high cycle life that little depends on winding or sewing (92%, 99% after 10,000 cycles, respectively) are important for application in electronic textiles.

9056-77b

Mechanism of stroke enhancement by coiling in carbon nanotube hybrid yarn artificial muscles

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Twisted carbon nanotube (CNT) yarns have been shown to develop useful torsional and tensile actuation when stimulated electrochemically, thermally, photonically or chemically. Particularly useful are those hybrid yarns that incorporate a volume-changing guest material into the yarn pore space. Changing guest volume causes concomitant untwisting and shortening of the twisted yarn. Intriguingly, the magnitude of the tensile actuation can be increased by an order of magnitude by inserting such high twist into the fiber as to cause coiling.

The mechanism of coil-induced stroke enhancement is investigated using ordinary spring mechanics. Stretching a helically coiled spring will induce a twisting of the spring wire. According to Love (1892), the change in wire twist (ΔT) is related to the change in coil bias angle (?) and diameter (D): ΔT=[sin(?')cos(?')]/πD'-[sin(?)cos(?)]/πD

This relation is shown to successfully demonstrate how relatively small changes in fiber twist can induce large changes in coil bias angle and coil length. These results indicate that tensile actuation in helically coiled hybrid CNT yarns can be maximized by increasing the extent of torsional actuation. High twist insertion and high volume change favor large torsional rotations.

9056-78b

Artificial muscles on heat

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There are many applications where low grade waste heat is produced. Some of these include combustion engines, electrical circuits, biological processes and industrial processes. To capture this heat energy thermoelectric devices, using the Seebeck effect, are commonly used. However these devices have limitations in efficiency, and usable voltage. This paper investigates the viability of a Stirling engine coupled to an artificial muscle energy harvester in order to efficiently convert waste heat energy into electrical energy.

The prototype Stirling engine's displacer sub-system converts thermal energy from a low-temperature differential source into mechanical work in the form of pressure and volume fluctuations of a working gas. The cyclic pressure source is directly coupled to a dielectric elastomer artificial muscle energy harvester, forming a thermo-mechanical-electric generator. Dielectric elastomer generators have considerable promise for harvesting this energy since they have few moving parts and can be directly coupled to the engine's large-stroke, low-frequency motions.

The results present the testing of the prototype Dielectric Elastomer-Stirling Generator, including the optimisation of the resonant dielectric elastomers, generated power outputs and discuss future paths to optimising the generator's performance. This work has produced the first Dielectric Elastomer-Stirling Generator, and presents new methods for seeking an improvement over alternate thermo-mechanical-electric generators.

9056-79b

Artificial muscles based on coiled carbon nanotube yarns

Márcio D. Lima, Ray H. Baughman, The Univ. of Texas at Dallas (United States)

Our recent work [1] has shown that coiled carbon nanotube (CNT) hybrid yarns have great potential as highly reversible, fast, strong and with large-stroke tensile and torsional actuators . This new class of artificial muscles have several potential applications such as lighter and faster actuators for robotics, nano-medicine, MEMS, energy harvesting, smart materials and textiles. The two main mechanisms for actuation in coiled artificial muscles are the expansion of the active material driven by either thermal expansion or absorption of molecules or ions. Absorption driven actuation shows great promise for development of more energetically efficient and biocompatible actuators since it can operate isothermally. We have recently advanced our artificial muscles by using absorption driven actuation in coiled CNT yarns which are capable to deliver up to 50% of tensile contraction, operate under tensile stresses up to 100 MPa and contract in less than 0.2 seconds. The same coiled CNT yarn can also actuate when driven by electricity or by light.

[1] M. D. Lima et al., Electrically, Chemically, and Photonically Powered Torsional and Tensile Actuation of Hybrid Carbon Nanotube Yarn Muscles. Science 338 (2012) 928.

9056-80b

Automated manufacturing process for DEAP stack-actuators

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Dielectric elastomers are thin polymer films belonging to the class of electroactive polymers, which are coated with compliant and conductive electrodes on each side. Due to the influence of an electrical field, dielectric electroactive polymers perform a large amount of deformation. Because single-layer actuator films are not suitable for positioning applications, novel energy-efficient multilayer-actuators are utilized to enlarge the absolute displacement and force at a consistent high strain. For the multilayer-technology many actuator films are mechanically connected in series, building up a stack actuator, which elongates in case of a charged EAP capacitance.

This contribution deals with the development, construction and realization of an automated manufacturing process for DEAP stack-actuators. First of all the developed topology of the considered stack-actuator and afterwards the concept, construction and realization of the automated fabrication is presented.

In contrast to known chemical stacking processes, thin DEAP-films are mechanically stacked in series ensuring a low driving voltage due to the electrical connection in parallel. In order to obtain a modular and flexible construction, the whole process is divided into several steps, which can be adapted separately to produce various actuator geometries by an

automated manufacturing process. Due to the very thin DEAP-films, the films are folded to facilitate the handling in a first step. In the next steps the folded DEAP-films are stacked, cutted, contacted and encapsulated. By applying this automated process, stack actuators with reproducible and homogeneous properties are manufactured. Finally, the fabricated DEAP actuator modules are validated experimentally.

9056-81b

Polypyrrole as a precursor of choice for micromanufacturing of microelectrodes

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Polypyrrole (PPy) grown in the template of patterned photoresist is used to build multi-layered electrodes. These electrodes have very high surface area per footprint (thus appropriate for use in microdevices) and precise control of geometric dimensions allows optimization of high surface area and low resistive losses in the three-dimensional structure. Contact resistance is also minimized by the fact that all the layers and supporting pillars of the multi-layered electrode are made from the same PPy material. Versatility of this technique includes co-deposition and entrapment of the enzymes (such as glucose oxidase) to create high sensitivity biosensors. The three-dimensional electrodes have been demonstrated to be very effective for positive or negative dielectrophoretic (DEP) particle separations and combination of positive DEP and electropolymerization of PPy allows for entrapment of particles and cells on the surface of electrodes, leading to additional functionalities of these electrodes. Polypyrrole can be converted to carbon via pyrolysis at 900?C in nitrogen environment. Carbon is widely used electrode material due to its conductivity and its wide window of electrochemical stability. We report on comparison of carbon layers fabricated via pyrolysis of polypyrrole and poly-aniline for several deposition conditions.

9056-82b

3D printing for dielectric elastomers

Andrew S. Creegan, Iain A. Anderson, The Univ. of Auckland (New Zealand)

Imagine an artificial heart that is fully formed from polymer materials and soft actuators, and attached directly to a patient's own circulatory system, or a soft robot with animal-like polymer muscles each inherently capable of complex proprioceptive feedback. The future of Dielectric Elastomers lies in these applications. Today, DE manufacturing techniques are labor intensive and limited only to planar devices; not the complex 3D geometries of the heart or of skeletal muscles. However, a fast growing technology with the ability to manufacture complex shapes using polymers already exists: 3D printing. Complex geometries present no problems for 3D printers, and the process is completely automated.

There are many 3D printing technologies, but the most suited for adaption to high resolution DE production would be Stereolithography. This prospect presents one main challenge: DEs are made of two materials, an elastomer and an electrode. Ordinarily, Stereolithography cannot be used for two materials since contamination between the two supplies of material would occur. We have developed a method for Stereolithography printing with two separate supplies of plastic, and will discuss how this could be adapted to printing with the liquid silicone materials used in DEs, paving the way for 3D printing of Dielectric Elastomers.

9056-83a

Electromechanical and electro-optical properties of PEDOT based IPNs *(Invited Paper)*

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Conducting IPN devices are based on high molecular weight NBR, PEO derivative and PEDOT. The way of synthesis allows an inhomogeneous distribution of PEDOT across the sample thickness, leading to a pseudo trilayer configuration. After swelling with an ionic liquid and applying an alternative low voltage between the two sides of the film, this device can work as an actuator or as an infrared switching electro-emissive device according to the PEDOT content.

Conducting IPN behaves as an actuator when the PEDOT content (i.e. the electroactive polymer) is close to 20wt%. Actuation performances under electrical stimulus have been characterized in open air in a two electrode configuration. Actuators exhibit a maximum strain value of 2% with an output-force of 30 mN. When the actuator thickness is decreased the actuation frequency increases. Ultrathin actuators can operate at high frequency (above 100Hz) while producing a large displacement at the mechanical resonance.

For a lower PEDOT content (around 3wt%), the device shows interesting optical properties in the infrared region between 5 and 50 ?m. The device exhibits switching properties as notably a maximal emissivity contrast of 0.31 with a switching time less than 3 min in low vacuum . These electroactive materials can be used as active materials for spacecraft thermal control.

9056-84a

In situ measurements with CPC micro-actuators using SEM

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Carbon-polymer composite (CPC) micro-actuators with ionic liquid electrolyte capable of operation under high vacuum were studied in situ using scanning electron microscope (SEM). Constructed CPC actuators are composed of titanium carbide-derived carbon (TiC-CDC) as an active electrode material, 1-ethyl-3-methylimidazolium tetrafluoroborate (EMIBF4) as an electrolyte and polyvinylidene fluoride-co-hexafluoropropylene (PVdF(HFP)) as an electrode binder and a separator. The actuators were prepared using layer-by-layer casting and subsequent hot-pressing. Low vapor pressure, non-flammable character and wide electrochemical window make ionic liquids favorable solvent-free electrolytes for ionic actuators working under wide range of environmental conditions. Fabricated micro-actuators sustained their actuation performance in high vacuum, enabling to use scanning electron microscopy (SEM) for electromechanical characterization. SEM observations demonstrate high stroke actuation of a completed device with sub-millimeter length, which is the typical size range of actuators desirable for medical or lab-on-chip applications. In situ SEM observation enables direct measurement of the anisometric expansion character in several levels – from the measurement of size variations of individual TiC-CDC particles separately to the estimation of the proportion of volumetric expansion between the electrodes and the separator. In addition, high resolution in situ images reveal the location of the neutral plane in the actuator. The SEM observations are finally compared to the results

obtained by electrochemical dilatometry as a facile method to correlate strain with applied voltages / charges of electrochemical materials.

9056-85a

Evaluation of area strain response of dielectric elastomer actuator using image processing technique

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Dielectric elastomer actuator (DEAs) is a kind of soft actuators that can produce significantly large electric-field induced actuation strain and may be basic unit of artificial muscles and robotic elements. Understanding strain development on a pre-stretched sample at different regimes of electrical field is essential for potential applications. In this paper we report about ongoing work on determination of area strain using digital camera and image processing technique. The setup, developed in house consists of low cost digital camera, data acquisition and image processing algorithm. Samples have been prepared by biaxially stretched acrylic tape and supported between two cardboard frames. Carbon-grease has been pasted on the both sides of the sample, which will be compliant with electric field induced large deformation. Images have been grabbed before and after the application of high voltage. From incremental image area, strain has been calculated as a function of applied voltage on a pre stretched dielectric elastomer (DE) sample. Area strain has been plotted with the applied voltage for different pre stretched samples. Our study shows that the area strain exhibits nonlinear relationship with applied voltage. For same voltage higher area strain has been generated on a sample having higher pre-stretched value. Also our characterization matches well with previously published results which have been done with costly video extensometer. Hyperelastic models (Yeoh, Ogden and Mooney Rivlin) are verified by comparing calculation results with the experimental observations. Excellent agreement is obtained between the experimental results and developed polynomial model. The study will be helpful for the designers to fabricate the biaxial prestretched planar actuator for similar kind of materials.

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9056-86a

Stability, failure, voltage-induced deformation and temperature change of dielectric elastomers

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Dielectric elastomer is a kind of typical soft active material. It can undergo large deformation when subject to an electric field. Dielectric elastomers usually fail because of the onset of electromechanical instability, snap-through instability and electrical breakdown. If the electromechanical instability, snap-through instability and electrical breakdown can be avoided, the large deformation can induce adiabatic temperature change and isothermal entropy change of the dielectric elastomer. We investigated the stability (electromechanical stability, snap-through stability), failure (electrical breakdown, loss of tension, rupture, instability), voltage induced deformation, entropy change and temperature change of dielectric elastomers. With the influence of temperature taken into consideration, we developed the temperature, polarization and deformation coupling thermodynamical free energy model to calculate the electric field induced deformation, adiabatic temperature change and isothermal entropy change of dielectric elastomers. These simulation results should offer great help in guiding the design and fabrication of excellent transverter base on dielectric elastomers.

9056-87b

Approaches to soft electronic skin *(Invited Paper)*

Ingrid M. Graz, Johannes Kepler Univ. Linz (Austria)

In an aquarium visitors will be inevitably drawn to the fish tank of the octopus. The octopus never fails to amaze people with its ability to squeeze into the tightest hole, grab and open bottles and hide itself from prying eyes by changing its color. All these abilities are highly favorable for soft robotics as they offer cheap, safe and well-adapted solutions for prostheses, implants, medical and cooperative robotics. Here the concept of phase-change triggered elastomer actuators is exploited where a liquid is evaporated by means of resistive heating. Simple robotic limbs achieve forces up to 6 N with multiple gaits.

An octopus uses its arms to explore its surroundings by touching it, its skin providing sensory feedback to touch, texture, pressure, and temperature. Our approach to stretchable artificial electronic skin employs the concept of wrinkles, also familiar from human skin, enabling large uni- and biaxial deformations without compromising the electrical functionalities. An ultra-thin polymer foil supported by a thick rubber layer forms the platform for stretchable conductors and electronic circuits. We have demonstrated reliability of conductors and devices such as thin film transistors and OLEDs up to 10.000 cycles.

When stalking prey or hiding, the octopus changes its color by enlarging pigmented areas on its skin. Polymer opals change their color according to strain as the lattice spacing within the artificial photonic crystal is altered. Visual and haptic feedback is provided by means of the phase-change actuator. Alternative concepts using snap-through instabilities in gas and water-filled balloons are investigated.

9056-88b

Artificial heart for humanoid

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A soft robotic device inspired by the pumping action of a biological heart is presented in this study. Developing artificial heart to a humanoid robot enables us to make a better biomedical device for ultimate use in humans. As technology continues to become more advanced, the methods in which we implement high performance and biomimetic artificial organs is getting nearer each day. In this paper, we present the design and development of a soft artificial heart that can be used in a humanoid robot and simulate the functions of a human heart using shape memory alloy technology. That robotic heart is designed to pump a blood-like fluid to parts of the robot such as the face to simulate someone blushing or when someone is angry by the use of elastomeric substrates and certain features for the transport of the fluids.

9056-89b

Towards a deployable satellite gripper based on multisegment dielectric elastomer minimum energy structures

Oluwaseun A. Araromi, Irina Gavrilovich, Jun Shintake, Samuel

Rosset, Herbert R. Shea, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Dielectric elastomer actuators (DEAs) are an emerging actuation technology which are inherent lightweight and compliant in nature, enabling the development of unique and versatile devices, such as the dielectric elastomer minimum energy structures (DEMES). We present the development of a multisegment DEMES actuator for use in a deployable micro satellite gripper. The inherent flexibility and lightweight nature of the DEMES actuator enables space efficient storage (e.g. in a rolled configuration) of the gripper prior to deployment. Multissegment DEMES have multiple open sections and are an effective way of amplifying bending deformation in high aspect ratio actuators. To achieve high accuracy, repeatability and robustness we employ the use of blade casted silicone membranes and pad printed electrodes. The optimization of our multisegmet DEMES design and fabrication process is thus presented here, including the trade-off between using multiple single segment actuators linked together or a single frame with multiple open sections. Three design approaches are proposed and evaluated qualitatively. One fabrication approach was selected for experimentation; the results of this methodology and of two subsequent design iterations are given. The prototype actuators weigh a maximum of 0.65 g and are robust and mechanically resilient demonstrating over 80,000 activation cycles after being stored in a rolled state. We also show the characterization of our actuators in terms of bending angle for a given input voltage and gripping force.

9056-90b

The mechanical design of a humanoid robot with flexible skin sensor for use in psychiatric therapy

Alec R. Burns, Manoj Kumar Palanisamy, Yonas T. Tadesse, The Univ. of Texas at Dallas (United States)

In this paper, a humanoid robot is presented for ultimate use in the rehabilitation of children with mental disorder such as autism. Creating affordable and efficient humanoid could assist the therapy in psychiatric disability by offering multimodal communication between the humanoid and humans. Yet, the humanoid development needs seamless integration of artificial muscles, sensors, controller and structures. We have designed a human-like, full humanoid robot that has 15 DOF, and a mobile platform using rapid prototyping system. The robot has a human-like appearance and movement and equipped with flexible sensors around the arm and hands for safe human-robot interactions. The robot has facial features for illustrating human-friendly behavior. The mechanical design of the robot and the characterization of the flexible sensors for areal sensing of the body are presented. The design concept; upper body design, mobile base, actuator selection at joints, electronics, and evaluation are included in this paper. It has a 580 mm height and a 925 mm arm span.

9056-91b

Modeling of a PVDF-based gesture controller using energy methods

Kyle Van Volkinburg, Gregory Washington, Univ. of California, Irvine (United States)

This paper focuses on the design and development of a gesture controller to be worn on the forearm using discretely located polyvinylidene fluoride (PVDF) patches as sensors. Computes, stereos, TVs, and video game counsels are all examples of devices that require user inputs from an array of controllers. With the development of the gesture controller it would be possible to use intuitive gestures and a single controller across multiple platforms. PVDF was selected as the sensing mechanism because of its well understood electromechanical characteristics as well as its ease of implementation. Discrete PVDF patches were attached to a forearm compression sleeve to detect muscle motion associated with hand gestures. The gesture controller was designed using dSPACE to understand optimal patch location and signal processing. The gesture controller was then implemented as a computer presentation tool using an Arduino Leonardo where it replaced mouse clicking with a designated hand gesture. The goal of this research is to take what was learned using discreet PVDF patches and develop a more complex controller using a single continuous PVDF sensor using shading techniques to accurately identify muscle motion in the forearm.

9056-92b

Multi degree of freedom IPMC sensor

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Ionic polymer-metal composite (IPMC) has been examined through simulation and experimental verification as a material for use in multi degree of freedom (DOF) sensor applications. Mechanoelectrical transduction, the ability to generate current from imposed mechanical deformation, enables IPMCs to be applied as sensor devices. This phenomenon has been reported and is reasonably well described by various models. In this study, a physics based model is applied to predict performance of an IPMC sensor over a range of conditions. Configuration of our interest is cylindrical IPMC with 2-DOF mechanoelectrical sensor capabilities. The prototype of cylindrical IPMC has a diameter of 1 mm and a 20 mm length. Application of deformation induced voltage of the fabricated cylindrical IPMCs as a means of mechanoelectrical transduction have been simulated and experimentally verified. The performance of the prototype IPMC under several operating conditions was also analyzed, and experimental results have provided keen insight into the physical phenomenon of mechanoelectical IPMC transduction.

9056-93b

Optimal haptic feedback control of artificial muscles

Daniel Chen, Thor Besier, Iain A. Anderson, Thomas G. McKay, The Univ. of Auckland (New Zealand)

As our population ages, and trends in obesity continue to grow, joint degenerative diseases like osteoarthritis (OA) are becoming increasingly prevalent. With no cure currently in sight, the only effective treatments for OA are orthopedic surgery and prolonged rehabilitation, neither of which is guaranteed to succeed.

Gait retraining has tremendous potential to alter the contact forces in the joints due to walking, reducing the risk of one developing hip and knee OA. Dielectric Elastomer Actuators (DEAs) are being explored as a potential way of applying intuitive haptic feedback to alter a patients' walking gait. The main challenge with the use of DEAs in this application is producing large enough forces and strains to induce sensation when coupled to a patient's skin.

A novel controller has been proposed to solve this issue. Using simultaneous capacitive self-sensing and actuation, we have the ability to optimally apply a haptic sensation to the patient's skin without the variability inherent in DEA, attachment and patient geometries affecting this optimization.

9056-94b

Soft segmented inchworm robot with dielectric elastomer muscles

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Robotic devices typically utilize rigid components in order to produce precise and robust operation. Rigidity becomes a significant impediment, however, when navigating confined or constricted environments e.g. search-and-rescue, industrial pipe inspection. In such cases adaptively conformable soft structures become optimal. Dielectric elastomers (DEs) are well suited for developing such soft robots since they are inherently compliant and can produce large muscle-like actuation strains. In this paper, a soft segmented inchworm robot is presented that utilizes pneumatically-coupled DE membranes to produce inchworm-like locomotion. The robot is constructed from repeated body segments, each with a simple control architecture, so that the total length can be readily adapted by adding or removing segments. Each segment consists of a soft inflatable shell (internal pressure in range of 1.0-15.9 mBar) and a pair of antagonistic DE membranes (VHB 4905). Experimental testing of a single body segment is presented and the relationship between drive voltage, pneumatic pressure and active displacement is characterized. This demonstrates that pneumatic coupling of DE membranes induces complex non-linear electro-mechanical behaviour as drive voltage and pneumatic pressure are altered. Locomotion of a two-segment inchworm robot prototype with a passive length of 80 mm is presented. Artificial setae are included on the body shell to generate anisotropic friction for locomotion. A maximum locomotion speed of 4.1 mm/s was recorded at a drive frequency of 1.5 Hz, which compares favourably to biological counterparts. Future development of the soft inchworm robot are discussed including reflexive low-level control of individual segments.

9056-95c

Niobium nanowire yarns and their application as artificial muscle

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Since the discovery of carbon nanotubes, various devices have been made in different fields of science and engineering. The mechanical and electrical properties that carbon nanotubes offer make them a great candidate for use in the structure of artificial muscles. In this thesis, for the first time, we have demonstrated that metallic nanowires can be engineered to become strong and comparable to the CNT yarns in mechanical and electrical properties. The niobium yarns offer conductivity of up to 3?10? S m-?, tensile strength of up to 1.1 GPa and Young's modulus of 19 GPa. The niobium nanowire fibres are fabricated by extracting the niobium nanowires from copper-niobium nano-composite matrix, which was made by using a severe plastic deformation process. As a practical application, torsional artificial muscles were made out of the niobium yarns by twisting and impregnating them with paraffin wax. Upon applying voltage to the twisted yarn the wax melts and expands due to the heat generated by the current. Thermal expansion of wax untwists the yarn, which translated to torsional actuation. Torsional speeds of 7,200 RPM (in a destructive test) and 1,800 RPM (continuous) were achieved. In addition to torsional actuation, niobium yarns also can provide up to 0.24% of isobaric tensile actuation along the yarn's axis at 20 MPa load. Due to the high conductivity of the niobium yarns, the actuator can be made to actuate by even one single 1.5 V battery (for a 1 cm of niobium yarn).

9056-96c

A tuneable RF phase shifter driven by dielectric elastomer actuators

Oluwaseun A. Araromi, Pietro Romano, Samuel Rosset, Julien Perruisseau-Carrier, Herbert R. Shea, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

We present the successful operation of the first dielectric elastomer actuator (DEA) driven tuneable RF phase shifter. The development of dynamically reconfigurable microwave/ millimeter-wave (MW/ MMW) devices and antenna is becoming a prime need in the field of telecommunications and sensing. The real time updating of antenna characteristics such as coverage or operation frequency is particularly desired. Our tuneable phase shifter consists of metallic strips suspended a fixed distance over a co-planar waveguide by planar DEAs. The planar actuators must displace the metallic strips in-plane by approximately 500 ?m to achieve the desired phase shift. A 50 ±5 ?m vertical spacing is required between the waveguide and the metallic strips and these two components must be parallel to each other to within approximately 3°. Our current device is approximately 60 mm ? 60 mm in planar dimensions and meets the displacement requirements at only 70% of the maximum nominal electric field applicable. The demanding alignment and spacing criteria are incorporated and met in the device design. We observed phase shifting at approximately 30 GHz closely matching numerical simulations.

9056-97c

A novel duct silencer by using dielectric elastomer absorbers

Zhenbo Lu, Yongdong Cui, Jian Zhu, National Univ. of Singapore (Singapore)

A novel duct silencer was developed by using dielectric elastomer absorbers (DEA). Dielectric elastomer, a lightweight, high elastic energy density and large deformation under high DC/AC voltages smart material, was used to fabricate this new generation actuator. The performance of duct silencer with DEA was experimentally investigated in the present paper. It was found that this new duct silencer could absorb wider range noise than the conventional silencer, furthermore, the absorption could be controlled by inputting various control voltages. The results also provide insight into the appropriateness of the absorber for possible use as new acoustic treatment for replacing the traditional acoustic treatment.

9056-98c

Artificial vibrissae DEA-based module

Tareq Assaf, Andrew T. Conn, Jonathan M. Rossiter, Peter J. Walters, Martin J. Pearson, Bristol Robotics Lab. (United Kingdom)

The article presents an active whisker structure based on Dielectric Elastomer Actuators (DEAs). The work aims to exploit the advantageous features of DEA technology, for effective and reliable robotic applications, and to address some of the disadvantages of this emerging actuation technique. To this end, a modular design and structure have been conceived in order to simplify the build and repair processes of critical components, such as; connections, wiring, sensors and DEA membrane failures. The design constitutes a significant extension to previous works on artificial whiskers by overcoming some of the technical and methodological constraints preventing adoption into real applications. For example, screws have been replaced by a series of magnets to provide both structural integrity and power directly to the membrane by the structure itself. The structure is realised as a trade-off between the unique characteristics of the DEA technology and the robotic development issues. Similarly the safety, robustness, production time and other key aspects of robotic design were taken into account in the development of this prototype. The results show how this structure meets the original design requirement for an active whisking range of ±14 degrees (measured using image processing of video captured from both standard and high speed cameras). This measure of performance will be used to guide future improvements that are discussed, along with the advantages and limits of the structure and the choices that were made.

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9057-1

Global nonlinear electroelastic dynamics of a bimorph piezoelectric cantilever for energy harvesting, sensing, and actuation

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Inherent nonlinearities of piezoelectric materials are inevitably pronounced in various engineering applications such as sensing, actuation, their combined applications for vibration control, and most recently, energy harvesting from dynamical systems. The existing literature focusing on the dynamics of electroelastic structures made of piezoelectric materials have explored such nonlinearities in a disconnected way for the separate problems of mechanical and electrical excitation such that nonlinear resonance trends have been assumed to be due to different additional terms in constitutive equations by different researchers. Similar manifestations of softening nonlinearities have been attributed to purely elastic nonlinear terms, coupling nonlinearities, or both of these effects, by various authors. However, a reliable nonlinear constitutive equation for a given piezoelectric material is expected to be rather unique and valid regardless of the application, e.g. energy harvesting, sensing, or actuation. A systematic approach focusing on the two-way coupling can result in a sound mathematical framework. To this end, the present work investigates the nonlinear dynamic behavior of a bimorph piezoelectric cantilever under low-to-high mechanical and electrical excitation levels in energy harvesting, sensing, and actuation. A mathematical framework is developed by using the method of harmonic balance to identify and validate the nonlinear system parameters.

9057-2

Feasibility study of a two-dimensional vibration energy harvester with frame configuration

Hao Wu, Lihua Tang, Yaowen Yang, Chee Kiong Soh, Nanyang Technological Univ. (Singapore)

Vibration energy harvesting using piezoelectric material is a promising solution for powering small electric devices, which has attracted great research interest in recent years. Numerous efforts have been done by researchers to improve the efficiency of vibration energy harvesters (VEHs) and to broaden their bandwidths. In most reported literature, VEHs are designed to harvest energy from a vibration source with a specific excitation direction. However, a practical environmental vibration source may include multiple components from different directions. Thus, it is an important concern to design a VEH to be adaptive to multiple excitation directions. In this article, a novel piezoelectric energy harvester with frame configuration is proposed to address this issue. It can work either in its vertical vibration mode or horizontal vibration mode. Therefore, the harvester can capture vibrations from arbitrary direction in the two-dimensional plane. According to the results obtained from finite element simulation, the resonant frequencies of its vertical and horizontal modes can be tuned to the same value. Thus, such a VEH can always provide significant output at any orientation of excitations at this tuned resonant frequency. Furthermore, experiment is performed to validate the simulation results. The development of two-dimensional VEHs in this study indicates their promising potential in practical vibration scenarios.

9057-3

Investigation of practical on-road energy harvester

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This paper introduces a new type of high power output on-road energy harvester. To achieve higher power output, instead of using piezoelectric material, mechanical energy harvester was investigated. When a vehicle runs over a harvester, the top plate of the harvester makes vertical directional motion, and this vertical motion of top plate rotates main shaft of the energy harvester through creatively designed cam. By adopting a one-way clutch between the cam and a main shaft, uni-directional rotation of the main shaft was achieved. In order to increase the efficiency of the harvester, the second one-way clutch was also implemented between the flywheel and gearbox. Once the force is conveyed from the gearbox to flywheel, the second one-way clutch disengages the flywheel from gearbox so that the flywheel does not affected by the frictions of gearbox and rest of the system. By designing the vertical directional displacement of the harvester as small as possible, this harvester doesn't require the vehicle to slow down when the vehicle runs over the harvester. Flywheel optimization analysis also has done to maximize the efficiency of the flywheel while the harvester remains in compact size. The electricity which is generated from this harvester can be used to power the road facilities such as street light, car speed indicator, and traffic signal.

9057-4

Optimal piezoelectric energy harvesting using elastoacoustic mirrors by frequency-wavenumber domain investigation

Matteo Carrara, Jason A. Kulpe, Stephen M. Leadenham, Michael J. Leamy, Alper Erturk, Georgia Institute of Technology (United States)

Recent work has demonstrated efficient transformation of structure-bone propagating waves into low-power electricity using metamaterial-inspired mirror configurations. Elastoacoustic waves originating from a point source as well as plane waves have been successfully focused to the piezoelectric energy harvester location using elliptical and parabolic mirror concepts made of periodic components, respectively. Our present work investigates the spatial optimization of a piezoelectric energy harvester domain weakly coupled to a thin plate housing an elastoacoustic mirror. Mirrors considered include elliptical arrangements of periodic stubs, and an elliptical arrangement of inclusion material. Spatial and temporal transformation of the wave field into the wavenumber-frequency space is followed by a frequency domain root-mean-square evaluation of the preferred directions in wavenumber domain. The harvester design process exploits a frequency-flattened wavenumber representation of the propagating wave field, and optimized material distributions are retrieved for rectangular and elliptical piezoelectric sensor configurations. Various case studies demonstrate performance enhancement of signal amplification and increased piezoelectric power generation for various mirror configurations, harvester topology, stub sizes, and material impedances.

9057-5

Durability of a piezo-composite electricity generating element in a d33 mode energy harvesting to impact loading

Vinh Tung Le, Van-Lai Pham, Konkuk Univ. (Korea, Republic of); Seong-Up Hwang, Konkuk Univ (Korea, Republic of); Nam Seo Goo, Konkuk Univ. (Korea, Republic of)

Recently, the use of a piezo-composite generating element (PCGE) for harvesting electric energy from ambient environment has been paid much attention in engineering field since the burning of fossil fuels causes environmental and health problems. Research has been performed with d31 and d33 mode energy harvesting of PCGE. However, the durability of PCGE for energy harvesting is rare. Therefore, in this research, d33 –mode PCGE-F was tested for its durability after a specific period time. To determine the performance of the proposed PGGE-F, a motor lever system was designed to apply the impact force on the PCGE's surface. ADAMS™ software was used to simulate the motor lever system to verify the concept of design. The output voltage of the PCGE-F was observed when the impact force was applied. The durability was considered with the variety of stress application. The durability of PCGE-F was investigated when the generated output voltage was decreased about 70%. The results showed that the impact frequency from ADAMSTM was in good agreement with that from experiment. This means that the motor lever system can be used to characterize the lifetime performance of PCGE-F. In addition, the lifetime of PCGE-F is inversely proportional to the stress application. In particular, with low stress application (around 0.76 MPa or lower), a decrease of PCGE performance is almost not significant change after 2 M cycles, as higher stress application (around 0.92 MPa or higher), the degradation occurs sooner (around cycles).

9057-6

Negative capacitance shunt damping system with optimized characteristics for use with piezoelectric transducers

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For ecologic sustainability and decreasing reserves of fossile energy sources, fuel efficiency is a major concern especially for passenger aircraft. Therefore, lightweight structures made from carbon fiber plastics offer great potential. But when used for panel-like structures, they have the disadvantage of lower damping and coincidence frequencies compared to conventional differential metal constructions. Both aspects lead to an increased vibration level and by this a higher noise radiation. Because of this, special noise and vibration treatment is needed to ensure passenger cabin comfort. Besides passive damping and active structural acoustics control (ASAC), shunt damping is investigated.

Due to its broadband performance, the negative capacitance shunt can be used for multimode systems with varying eigenfrequencies. These shunts are usually built with operational amplifiers and passive components as resistors and capacitors. This setup is sufficient for laboratory tests, but it is not capable of accessing the full voltage amplitude of common piezoelectric transducers, because most operational amplifiers only deliver ±15V maximum output voltage. Therefore an improved setup is presented in this paper, which addresses the specific voltage requirements of a commercial piezoelectric transducer to achieve best performance.

It comprises a tailored power source and an appropriate concept for the negative capacitance shunt hardware. This new hardware only uses standard operational amplifiers together with a high voltage power amplifier to cover the whole operating range of a piezoelectric transducer. A demonstrator board is developed and experimentally investigated at a test structure. Finally, the results are compared to a conventional setup.

9057-7

Development of vibration isolation platform for low amplitude vibration

Dae Oen Lee, Geeyong Park, Jae-Hung Han, KAIST (Korea, Republic of)

The performance of high precision payloads onboard a satellite is extremely sensitive to vibration. Although vibration environment of a satellite on orbit is very gentle compared to the launch environment, even a low amplitude vibration disturbances generated by reaction wheel assembly, cryocoolers, solar array drives, etc may cause serious problems in performing tasks such as capturing high resolution images and communicating at high-data rates. The most commonly taken approach to protect sensitive payloads from performance degrading vibration is application of vibration isolator. In this paper, development of vibration isolation platform for low amplitude vibration is discussed. Firstly, single axis vibration isolator that can achieve both the high roll-off rate and low Q-factor is developed by adapting three parameter model, which is realized using bellows and viscous fluid. The isolation performance of the developed single axis isolator is evaluated by measuring force transmissibility. The measured transmissibility shows that both the low Q-factor and the high roll-off rate are achieved with the developed isolator. Then, six single axis isolators are combined to form Stewart platform in cubic configuration to provide multi-axis vibration isolation. The isolation performance of the developed multi-axis isolator is evaluated using a simple prototype reaction wheel model as the vibration source. Transmitted force without vibration isolator is measured and compared with the transmitted force with vibration isolator.

9057-8

Optimal design of buildings subjected to near-fault earthquakes with S-FBI system using genetic algorithm

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This study investigates the optimum design parameters of a superelastic friction base isolator (S-FBI) system through a multi-objective genetic algorithm and performance-based evaluation approach. The S-FBI system consists of a flat steel-PTFE sliding bearing and a superelastic NiTi shape memory alloy (SMA) device. Sliding bearing limits the transfer of shear across the isolation interface and provides damping from sliding friction. SMA device provides restoring force capability to the isolation system together with additional damping characteristics. A five-story building is modeled with S-FBI isolation system. A neuro-fuzzy model is used to capture rate- and temperature-dependent nonlinear behavior of the SMA device. Multiple-objective numerical optimization that simultaneously minimizes isolation-level displacements and superstructure accelerations is carried out with a genetic algorithm (GA) in order to optimize S-FBI system. Nonlinear time history analyses of the building with S-FBI system are performed. A set of 20 near-field ground motion records are used in numerical simulations. Results show that S-FBI system successfully control response of the buildings against near-fault earthquakes without sacrificing in isolation efficacy and producing large isolation-level deformations.

9057-9

New strategy for the control of low frequency large band mechanical suspensions and inertial platforms

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In this paper we present the results of a theoretical and experimental study aimed to demonstrate both the feasibility and the advantages of a new control strategy based on the application of open loop monolithic folded pendulum sensors to the control of large band multistage suspensions (seismic attenuators) and inertial platforms to improve their performances in the low frequency band. In fact, the characteristics of compactness and robustness of this class of sensors, together with their small dimensions (< 10 cm), small weight (< 100 g), high sensitivity (< 10^-10 m/sqrt{Hz}), large measurement band (10^-7 - 100 Hz), resonance frequency tunability (70 mHz - 1 Hz, high sensitive integrated laser optical readout (e.g. optical lever, laser interferometer) and very good immunity to environmental noises make them good candidates, not only as stand-alone sensors or integrated within geographycally distributed networks for scientific applications, but also as control sensors.

For this task we have demonstrated, both theoretically and experimentally, that open loop monolithic folded pendulum sensors are very effective as sensors within the control system of a multistage mechanical suspensions (seismic attenuators) and inertial platforms, since they allow large improvements of the performances of these devices, especially in the low frequency band, and, at the same time, the introduction of new optimized control strategies. The results of this study are presented and discussed in this paper, together with the planned further developments and improvements.

9057-10

Multistable chain for ocean wave vibration energy harvesting

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The heaving of ocean waves is a largely untapped, renewable mechanical energy resource. Conversion of this energy into electrical power could integrate with solar technologies to provide for round-the-clock, portable, and mobile energy supplies for a wide variety of marine environments. However, the direct-drive conversion methodology of grid-integrated wave energy converters does not efficiently scale down to smaller, portable architectures. This research develops an alternative approach to harness the extraordinarily large heaving displacements and long oscillation periods as an excitation source for a long, extendible vibration energy harvesting chain. The proposed system links together a series of bistable cells. Individual impulse events are generated as the inertial mass of each cell is pulled across its region of negative stiffness to induce local snap through dynamics; the oscillating magnetic inertial mass then generates current through a coil which is fed to energy harvesting circuitry. Linking the cells into a chain transmits the impulses throughout the system leading to impulse and vibration cascades and therefore maximal electrical energy conversion. This paper describes the development of the multi-stable chain and ways in which realistic design challenges were addressed. Numerical modeling and corresponding experiments demonstrate the response of the chain due to slow and large amplitude input motion. Lastly, further experimental studies give clear evidence that the efficiency of the chain for wave energy conversion is much higher than using an equal number of bistable cells without connections.

9057-11

Electrohydroelastic dynamics of macro-fiber composites for underwater energy harvesting from base excitation

Shima Shahab, Alper Erturk, Georgia Institute of Technology (United States)

Low-power electronic systems are used in various underwater applications ranging from naval sensor networks to ecological monitoring for sustainability. In this work, underwater base excitation of cantilevers made of Macro-Fiber Composite (MFC) piezoelectric structures is explored experimentally and theoretically to harvest energy for such wireless electronic components toward enabling self-powered underwater systems. Bimorph cantilevers made of MFCs with different length-to-width ratios and same thickness are tested in air and under water to characterize the change in natural frequency and damping with a focus on the fundamental bending mode. The real and imaginary parts of hydrodynamic frequency response functions are identified based on this set of experiments and also compared with their numerical counterparts reported in the literature for different aspect ratios. An electrohydroelastic model is developed and experimentally validated for predicting the power delivered to an electrical load as well as the shunted underwater vibration response under base excitation. Variations of the electrical power output with excitation frequency and load resistance are obtained for different length-to-width ratios. Underwater power density results are reported and compared with their in-air counterparts.

9057-12

Flow energy piezoelectric bimorph nozzle harvester

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There is a need for a long-life power generation scheme that could be used downhole in an oil well to produce about 1 Watt average power. There are a variety of existing or proposed energy harvesting schemes that could be used in this environment but each of these has its own limitations. The vibrating piezoelectric structure is in principle capable of operating for very long lifetimes (decades) thereby possibly overcoming a principle limitation of existing technology based on rotating turbo-machinery. In order to determine the feasibility of using piezoelectrics to produce suitable flow energy harvesting, we surveyed experimentally a variety of nozzle configurations that could be used to excite a vibrating piezoelectric structure in such a way as to enable conversion of flow energy into useful amounts of electrical power. These included reed structures, spring mass-structures, drag and lift bluff bodies and a variety of nozzles with varying flow profiles. Although not an exhaustive survey we identified a spline nozzle/piezoelectric bimorph system that experimentally produced up to 3.4 mW per bimorph. This paper will discuss these results and present our initial analyses of the device using dimensional analysis and constitutive electromechanical modeling. The analysis suggests that an order-of-magnitude improvement in power generation from the current design is possible.

9057-13

Energy harvesting for self-powered aerodynamic control surfaces

Matthew J. Bryant, North Carolina State Univ. (United States); Matthew Pizzonia, Michael Mehallow, Ephrahim Garcia, Cornell Univ. (United States)

This paper will propose and experimentally investigate applying piezoelectric energy harvesting devices driven by flow induced vibrations to create a self-powered aerodynamic control surface for specialized aircraft applications. Recently, we have investigated flow-induced vibrations and limit cycle oscillations due to aeroelastic flutter phenomena in piezoelectric structures as a mechanism to harvest energy from an ambient fluid flow. We will describe how our experimental investigations in a wind tunnel have demonstrated that this harvested energy can be stored and used on-demand to actuate a control surface on a wing in the airflow such as a trailing edge flap. This actuated control surface could take the form of a separate and discrete actuated flap, or could constitute rotating or deflecting the vibrating energy harvester itself to produce a non-zero mean angle of attack. Such a rotation of the energy harvester and the associated change in aerodynamic force is shown to influence the operating wind speed range of the device, its LCO amplitude, and its harvested power output; hence creating a coupling between the device's performance as an energy harvester and as a control surface. Finally, the induced changes in the lift, pitching moment, and drag acting on the wing model are quantified and compared for the case of an oscillating, energy harvesting control surface and that of a traditional, rigid control surface of the same geometry.

9057-14

Ultrasound acoustic wave energy transfer and harvesting

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This paper investigates low-power electricity generation from ultrasound acoustic wave energy transfer combined with piezoelectric energy harvesting for wireless applications ranging from medical implants to naval sensor systems. The focus is placed on an underwater system that consists of a pulsating source for spherical wave generation and a harvester connected to an external resistive load for quantifying the electrical power output. An analytical electro-acoustic model is developed to relate the source strength to the electrical power output of the harvester located at a specific distance from the source. The model couples the energy harvester dynamics (piezoelectric device and electrical load) with the source strength through the acoustic-structure interaction at the harvester-fluid interface. Case studies are given for a detailed understanding of the coupled system dynamics under various conditions. Specifically the relationship between the electrical power output and system parameters, such as the distance of the harvester from the source, dimensions of the harvester, level of source strength, and electrical load resistance are explored. Sensitivity of the electrical power output to the excitation frequency in the neighborhood of the harvester's underwater resonance frequency is also reported. Results from proof-of-concept experiments are also discussed for model validation.

9057-15

Energy harvesting measurements from stall flutter limit cycle oscillations

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Experiments involving the use of an electromagnetic-inductor device to convert aeroelastic-induced oscillations of an airfoil into electricity were performed. The energy harvesting device consists of three magnets in which one magnet floats between two fixed magnets. The force-displacement relationship of the harvester is best described by a fifth-order polynomial. The integration of the harvester into a two-degree-of-freedom (pitch/plunge) airfoil system introduces nonlinear stiffness into the vertical (plunge) direction. Airspeeds were determined at which limit cycle oscillations (LCO) were excited by initial (pitch or plunge) displacements. For an initial set of tests, the harvester was disconnected from the airfoil flutter system which removed the nonlinear (plunge) stiffness. A critical flutter speed of approximately 55 mph measured. When the harvester was attached (introducing nonlinear stiffness into the plunge direction), the critical flutter speed increased to approximately 85 mph. Above this speed, LCO's were measured with pitch angle displacements greater than the stall angle (on the order of 0.5 rad) and are therefore attributed to stall flutter behavior. The LCO oscillations are converted into electric power (P = I2R) across a load resistor by the electromagnetic-inductor device. The influence of system parameters, including the nonlinear plunge stiffness, on power generation was investigated.

9057-16

Climbing robot actuated by meso-hydraulic artificial muscles

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This paper will present the design, construction, experimental characterization, and system testing of a legged, wall-climbing robot driven by meso-scale hydraulic artificial muscles. A modular four limb climbing robot platform that includes a full closed-loop hydraulic power and control system, custom hydraulic artificial muscles for actuation, an on-board microcontroller and RF receiver for control, and compliant, semi-passive claws for gripping a variety of wall surfaces has been constructed and is currently being tested to investigate this actuation method. On-board power consumption data-logging during climbing operation as well as subsystem experimental characterization of the motor and pump system efficiency and artificial muscle force-displacement characterization will be presented to evaluate the performance of this actuation method.

While wheels and tracks driven by electromagnetic motors are familiar designs for ground robot locomotion, legged platforms are advantageous for navigating rough terrain, climbing walls, and grasping to small toe-holds. The objective of this work is to investigate robot architectures that utilize lightweight hydraulic artificial muscles to enable efficient climbing robots. Using hydraulic actuation in a climbing robot is an attractive concept, but has received little research attention to date because the size and weight of traditional hydraulic systems are a poor match for small climbing robots. Hydraulic actuation can allow a single electric motor to drive a pump and power several degrees of freedom rather than performing electrical to mechanical transduction with a motor at each joint. This can allow the transducer to be driven at its peak efficiency and reduce system weight.

9057-17

Study of a bio-mimic spider web

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The goal of this study is to investigate dynamic properties and energy absorption capability of a bio-mimic spider web. An artificial spider web has unique mechanical properties that can inspire engineering applications, such as bullet proof vest and space web to catch high speed space trash.

To better understand the relationship between such capabilities of spider web and its web parameters, the effect of preload, radial and spiral silk stiffness and damping ratio on the natural frequency and energy of the web were examined experimentally and numerically. Different types of webs materials and configurations including damaged webs have been studied. It is shown how adjusting the web's mechanical properties such as the preload, stiffness and damping ratio can affect the natural frequency and energy absorption capability of full and damaged webs. Also, it is demonstrated that increasing preload can compensate for damaged wires of the artificial spiderweb.

9057-18

Resonant ultrasonic wireless power transmission for bio-implants

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Supplying electric power for biomedical implants is a very important subject. Virtually all medical implants are mainly powered by batteries. However, as the implant devices get smaller, these facts make them less attractive as the main power source. Therefore alternative techniques of energizing implantable micro-devices are needed. Energy transmission from external power source into a smaller rechargeable battery is an attractive alternative to conventional non-rechargeable batteries in low-power biomedical implants and has received increasing research interest in recent years.

In this paper, we propose the ultrasonic wireless power transmission system as a part of a brain-machine interface (BMI) system in development to supply the required electric power. Making a small-size implantable BMI, it is essential to design a low power unit with a rechargeable battery. The ultrasonic power transmission system has two piezoelectric transducers, facing each other between skin tissues converting electrical energy to mechanical vibrational energy or vice versa. Ultrasound is free from the electromagnetic coupling effect and medical frequency band limitations which making it a promising candidate for implantable purposes.

In this paper, we present the design of piezoelectric composite transducer, rectifier circuit, and rechargeable battery that all packaged in biocompatible titanium can. An initial prototype device was built for demonstration purpose. The early experimental results demonstrate the prototype device can reach 50% of energy transmission efficiency in water medium at 20mm distance and 18% in animal skin tissue at 17mm, respectively.

9057-19

A power electronics circuit for simultaneous semi-active vibration control and energy harvesting for electromagnetic regenerative suspensions

Peng Li, Lei Zuo, Chongxiao Zhang, Junyoung Kim, Stony Brook Univ. (United States)

Regenerative semi-active suspensions can capture the previously dissipated vibration energy and convert it to usable electrical energy for powering on-board electronic devices, while achieve both the better ride comfort and improved road handling performance at the same time. To achieve this function, the power electronics interface circuit connecting the energy harvester and the electrical loads, which can achieve simultaneous vibration control and power conditioning is in need. This paper proposed a power electronics interface circuit which is capable of simultaneous semi-active vibration control and energy harvesting for electromagnetic regenerative shock absorber. While performing the vibration control, the circuit always draw current from the energy harvester and remain dissipative, which means the energy always flows from the harvester to the load. An adaptive control scheme was applied on this circuit to respond to change of road excitation, while harvest energy at the same time. Two control signals were applied, one for vibration control, and the other for power conditioning. To overcome the unstable nature of the vibration energy, a buffer capacitor was applied between the input and output side of the circuit for energy accumulation and circuit protection. A prototype circuit was built and hardware-in-the-loop test was performed together with an electromagnetic shock absorber. Simulation and experiment results will be presented.

9057-20

Piezoelectric polarization in the design of a vibration energy harvester

James M. Gibert, Clemson Univ. (United States)

This manuscript is inspired by research showing that shear, d15, mode energy harvesters offer significant improvement in power generation over the traditional normal, d31, mode based harvesters. The premise behind this study is to examine the effect of expanding the design domain of PZT based energy harvesters by considering an arbitrary poling angle. In the first part of the manuscript, we used a Timoshenko model of an energy harvester to derive the governing equations of motion and power generated. The electric displacement depends on both the normal and shear strain. Thus the proposed device operates using a combination of shear and normal mode to extract power. The extent to which each mode is used depends on the polarization orientation. Additionally, the harvester is subject to a base excitation composed of both translational and rotational components. The resulting equations are solved using a Rayleigh Ritz analysis. We examine the effect of poling on the fundamental open and closed circuit frequencies of the system. Next, the poling angle is examined over a range to determine the effect on the power harvested at the fundamental modal frequencies of the system. Furthermore, for a given base excitation we derive the optimal poling. The study demonstrates that an arbitrary poled piezoelectric increases the power that the harvester produces over traditionally poled devices. Finally, we discuss the challenges in manufacturing the proposed harvester.

9057-21

Recent progress on micro-piezoelectric energy harvesters fabricated with aero-deposition and the interfacing circuits

Ya Shan Shih, Shun Chiu Lin, Wen Jong Wu, National Taiwan Univ. (Taiwan)

This paper presents a review of micro-piezoelectric energy harvester (MPEH) system based on MPEHs fabricated with an aero-deposited PZT technique, including both the device and the interface circuit design. The comparison between two different substrates, silicon and stainless steel, will be firstly discussed. Secondly, profound discussion on the cantilever structure and vacuumed packaging responses are shown. Thirdly, the non-linear synchronized switching technique interfacing circuit was designed to boost the harvested power in comparison to standard rectifying circuits. The boosting effect in comparison to theoretical expectations will be also presented. Experimental results show that the device based on silicon substrate showed a maximum output power of 21 ?W with the output voltage of 2.2 Vrms, excited at 215 Hz under a 1.5 g vibrating source. In comparison, the device based on stainless steel substrate, driven under the same acceleration, had a maximum output

power of 34 ?W with 1.8 Vrms at the resonant frequency of 202 Hz. The power densities were 4.7 ?W mm-2 and 7.6 ?W mm-2 for the silicon substrate and the stainless steel substrate based devices, each. The cantilever structured MPEG was later improved to the power output of 200.28 ?W. To further improve the output characteristic, the device was tested under vacuumed circumstance, which then gave the output power of 241.60?W, with a 6.02 Vrms under 1.5 g, 104.4Hz. The power boosting circuit gave a power gain of 2.03 times, as the overall system outputs 91.4 ?W using the self-powered nonlinear technique under 0.75 g with a similar device. The overall system, using only the standard rectifying circuit was able to light a low consumption red- colored SMD-0805 packaged LED in a duty ratio of approximately 25%.

9057-22

Synchronized charge extraction for aeroelastic energy harvesting

Liya Zhao, Lihua Tang, Hao Wu, Yaowen Yang, Nanyang Technological Univ. (Singapore)

Aeroelastic instabilities have been frequently exploited for energy harvesting purpose, including flutter, galloping, wake galloping and buffeting. Galloping-based energy harvesting has attracted more research attention due to its merits of large-amplitude of oscillations and capability of working in the infinite wind speed range. On the other hand, various energy harvesting interface circuits, such as synchronized charge extraction (SCE) and synchronized switching harvesting on inductor (SSHI), have been widely pursued in the literature for efficiency enhancement of energy harvesting from existing base vibrations. These interfaces, however, have not been applied for aeroelastic energy harvesting. This paper investigates the feasibility of the SCE interface in galloping-based piezoelectric energy harvesting, with a focus on its benefit for performance improvement and influence on the galloping dynamics in different electromechanical coupling regimes. A galloping-based piezoelectric energy harvester (GPEH) is prototyped with an aluminum cantilever bonded with piezoelectric elements. With different amount of piezoelectric elements connected, the coupling of the GPEH is altered. A self-powered SCE interface is implemented with the capability of self peak-detecting and switching. Wind tunnel test is conducted and circuit simulation is performed with equivalent circuit representation of the GPEH system. Both experiment and circuit simulation show that the harvested power with SCE interface for GPEH is independent of the electrical load, similar to that for a vibration-based piezoelectric energy harvester (VPEH). The dynamics of the harvester and thus the performance with SCE for GPEH is found more sensitive to the electromechanical coupling as compared to that for VPEH.

9057-23

Design of a new MR brake mount system considering vertical and horizontal vibrations

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In this paper, a new type of magnetorheological fluid (MRF) mount is proposed. This design is based on the well-known of two modes of MRF such as flow mode and shear mode. These modes are applied in the design which includes two components: MR mount for controlling vertical vibrations, and MR brake for controlling horizontal vibrations. The structure of MR valve is applied in design mount part, while the disk type of structure is employed in design brake part. These structures contribute to the initial requirements such as small structure, high damping force and high braking force. The theoretical analysis for the design is undertaken followed by design optimization using ANSYS ADPL software. The objective functions are concentrated on maximal damping force for MR mount and maximum braking force for MR brake. As traditional design, rubber mount is used in the proposed design for suffering static loads. It has been shown through computer simulation that the initial requirements with high damping force and high braking force have been successfully achieved.

9057-24

A variable stiffness and damping suspension system for high speed train

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As the vibration of high speed train becomes fierce when the train runs at high speed, it is crucial to develop a novel suspension system to negotiate train vibration. This paper presents a novel suspension based on Magnetorheological fluid (MRF) damper and multiple layer Magnetorheological elastomer (MRE) spring. The MRF damper is used to generate variable damping while the MRE spring is used to generate field-dependent stiffness. In this paper, the two kind smart devices, MRF dampers and MRE springs, are developed firstly. Then the dynamic performances of these two devices are tested by MTS. Based on the testing results, the mathematic models for MRF dampers and MRE springs are established in MATLAB/Simulink. Subsequently, the two devices are equipped to a high speed train which is built in ADAMS. The skyhook control algorithm is employed to control the novel suspension. In order to compare the vibration suppression capability of the novel suspension with other kind suspensions, three other different suspension systems are also considered and simulated in this paper. The other three kind suspensions are variable damping with fixed stiffness suspension, variable stiffness with fixed damping suspension and passive suspension. The simulation results indicate that the variable damping and stiffness suspension suppresses the vibration of high speed train better than the other three suspension systems.

9057-25

A bi-directional, controllable liquid-spring magnetorheological fluid damper

Nicholas Maus, Faramarz Gordaninejad, Univ. of Nevada, Reno (United States)

In this work a novel bi-directional and bi-linear controllable Liquid-Spring MagnetoRheological Fluid Damper (LS-CMRFD) is investigated. The proposed system has two functions in a single compact device, it is: 1) a liquid spring with significantly different compression and rebound reaction forces, 2) a tunable MRF damper. Theoretical and experimental studies were conducted to demonstrate the function of this system in a wide range of pre-loaded conditions and frequencies. The theoretical model is confirmed by experimental results. Sinusoidal quasi-static and dynamic experiments were conducted to investigate the performance of the LS-CMRFD at different input currents. The results show a significant change in spring and damping forces from the compression to rebound regions for both passive and MR damping.

9057-26

Magnetorheological impact seat suspensions for ground vehicle crash mitigation

Xian-Xu Bai, Hefei Univ. of Technology (China); Norman M. Wereley, Univ. of Maryland, College Park (United States)

Semi-active magnetorheological energy absorbers (MREAs) are one type of the most promising actuator for both the vibration and shock control. This paper investigates the frontal/rear crash mitigation performance of semi-active MR impact seat suspensions for ground vehicles. The

mathematical model of the MREAs is derived and the characteristics of the MREAs are theoretically evaluated and compared with each other with an identical volume. To explore the control effectiveness of MREAs in the shock isolation systems, the mechanical model of a 2-degree-of-freedom (2DOF) mitigation system with the MREAs are constructed. An optimal Bingham number control, which is to minimize the crash pulse loads transmitted to the occupants by utilizing maximum stroke of the MREAs based on pulse velocity, mass, and passive damping, is proposed and developed to improve the crash mitigation performance of the 2DOF MR seat suspension system. The simulated control performances of the mitigation systems based on the MREAs with different functional structures are evaluated, compared, and analyzed.

9057-27

Vibration energy harvesting using a spherical permanent magnet

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The Australian Defence Science and Technology Organisation (DSTO) is developing a variety of in-situ structural health monitoring (SHM) approaches for potential use in high value platforms across the Australian Defence Force (ADF). A critical issue is determining the optimal means of supplying power to these in-situ SHM systems. Recently a vibration energy harvesting approach has been reported that uses a wire-coil transducer to harvest energy from bi-axial vibrations. An oscillator was created using a spherical-permanent-magnet, wearpad and wire-coil arrangement. A magnetic restoring force acts on the magnet, and as the magnet oscillates it steers magnetic field through the transducer thereby producing an oscillating charge that can be harvested. The restoring force acting on the bearing is shown to be near linear for small amplitude bearing oscillations, and nonlinear for larger amplitude oscillations. Within prescribed limits the magnetic restoring force is well defined by a quintic polynomial, and hence the bearing's oscillatory motion (i.e. in the harvester) can be described using a forced Duffing equation. Approximate steady state resonant solutions of a forced Duffing oscillator are shown to compare well with measured bearing displacements, and can be used to predict the wideband frequency response and output power of this type of vibration energy harvester. A prototype harvester is described, which was found to produce a maximum output power of 11.5 mW from an 8 Hz, 100 milli-g excitation.

9057-28

Scaling of electromagnetic vibration energy harvesting devices

Genevieve A. Hart, Scott D. Moss, Defence Science and Technology Organisation (Australia)

The Australian Defence Science and Technology Organisation (DSTO) is developing a variety of in-situ structural health monitoring (SHM) approaches for potential use in high value platforms across the Australian Defence Force (ADF). A critical issue is determining the optimal means of supplying power to these in-situ SHM systems. A review of the vibration energy harvesting literature has been undertaken with the goal of establishing scaling laws for experimentally demonstrated harvesting devices. In particular electromagnetic harvesting devices are investigated. Power density metrics are examined with respect to scaling length, volume, frequency and drive acceleration. Improvements in demonstrated power density of harvesting devices over the past decade are noted. Scaling laws are found that appear to suggest an upper limit to the power density achievable with current harvesting techniques.

9057-29

Characterization of hybrid energy harvesting device consisting of piezoelectric and electromagnetic systems

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In this study, experimental characterizations of a new hybrid energy harvesting device consisting of piezoelectric and electromagnetic transducers are presented. The generator, to be worn on the legs or arms of a person, harnesses linear motion and impact forces from human motion to generate electrical energy from the two transduction systems in multimodal fashion. The device consists of an unbalanced rotor made of three piezoelectric beams which have permanent magnets attached to the ends. Impact forces cause the beams to vibrate, generating a voltage across their electrodes and linear motion causes the rotor to spin. As the rotor spins, the magnets pass over ten electromagnetic coils mounted to the base, inducing a current through the coils. Several design related issues were investigated experimentally in order to optimize the volumetric power density of the system for maximum power generation. Finite element based simulations were also conducted on the system to determine the capabilities of the device.

9057-30

Integration of regenerative shock absorber into vehicle electric system

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Energy harvesting shock absorbers (EHSA) have a great potential to increase fuel efficiency and provide suspension damping at the same time. Although intensive work on this topic has been done in recent years, the integration of EHSA into vehicle electric system, which is very important to realize the fuel efficiency benefit, has not been investigated. This paper is to study and demonstrate the integration of EHSA with vehicle alternator, battery and on-board electrical load together. In the presented system, the EHSA is excited by a shaker and it converts kinetic energy into electricity. The electrical energy then flows into a cascaded buck-boost converter. The converter realizes two functions: controlling the EHSA's damping and regulating the output voltage. The EHSA's damping is tuned by controlling its internal motor's current, which is also the input current of buck-boost converter. By adjusting the duty cycles of switches in the converter, its input impedance together with input current can be tuned according to dynamic damping requirements. A battery is connected to the output of buck-boost converter and the converter's cascaded topology promises the battery's proper charging. To simulate the working condition of combustion engine, an AC motor is used to drive a truck alternator, which is also connected to the battery. The battery supplies power resistors as electrical load. Experiment shows that as the buck-boost converter and truck alternator charge the battery and supply electrical load together, the power consumption of AC motor is reduced. This proves that the combustion engine's load is reduced and fuel efficiency is increased.

9057-31

Energy harvesting with coupled magnetostrictive resonators

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This work reports the investigation of an energy harvesting system composed of coupled resonators with the magnetostrictive material Galfenol (FeGa). A coupled system of meso-scale (1-10 cm) cantilever beams for harvesting vibration energy is described for powering and aiding the performance of low-power wireless sensor nodes. Galfenol is chosen in this work for its durability, compared to the brittleness often encountered with piezoelectric materials, and high magneto-mechanical coupling. A lumped model, which captures both the mechanical and electrical behavior of the individual transducers, is first developed. The values of the lumped element parameters are then derived empirically from fabricated beams in order to compare the model to experimental measurements. The governing equations of the coupled system lead to a system of differential equations with all-to-all coupling between transducers. An analysis of the system equations reveals different patterns of collective oscillations. Among the many different patterns, a synchronous state appears to yield the maximum energy that can be harvested by the system. Discussion of the required power electronics for such a coupled system are also included.

9057-32

A novel miniature thermomagnetic energy harvester

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Nowadays, thermal-energy-harvesting is an important research topic for powering wireless sensors. Among numerous thermal-energy-harvesting approaches, some researchers demonstrated novel thermomagnetic-energy harvesters to convert a thermal-energy from an ambient temperature-difference to an electrical-output to power the sensors. However, the harvesters are too bulky to be integrated with the sensors embedded in tiny mechanical-structures for some structural-health-monitoring applications. Therefore, miniaturized harvesters are needed. Hence, we demonstrate a miniature thermomagnetic-energy harvester. The harvester consists of CuBe-beams, PZT-piezoelectric-sheet, Gd-soft-magnet, NdFeB-hard-magnet, and mechanical-frame. The piezoelectric-sheet and soft-magnet is bounded at fixed-end and free-end of the beams, respectively. The mechanical-frame assembles the beams and hard-magnet. The length?width?thickness of the harvester is 2.5cm?1.7cm?1.5cm. According to this, our harvester is 20-times smaller than the other harvesters. In the initial-state of the energy-harvesting, the beams' free-end is near the cold-side. Thus, the soft-magnet is cooled lower than its curie temperature (Tc) and consequently changed from paramagnetic to ferromagnetic. Therefore, a magnetic-attractive force is produced between the soft-magnet and hard-magnet. Consequently, the beams/soft-magnet are down-pulled toward the hard-magnet fixed on the hot-side. The soft-magnet closing to the hot-side is heated higher than its Tc and subsequently changed to paramagnetic. Consequently, the magnetic-force is eliminated thus the beams are rebounded to the initial-state. Hence, when the harvester is under a temperature-difference, the beams' pulling-down/back process is cyclic. Due to the piezoelectric effect, the piezoelectric-sheet fixed on the beams continuously produces voltage-response. Under the temperature-difference of 29˚C, the voltage-response of the harvester is 30.4 mV with an oscillating-frequency of 0.098 Hz.

9057-101

A new method for speed control of a DC motor using magnetorheological clutch

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In this research, a new method to control speed of DC motor using magnetorheological (MR) clutch is proposed and realized. Firstly, the configuration of a DC motor speed control using MR clutch is proposed. The MR clutch configuration is then proposed and analyzed based on Bingham-plastic rheological model of MR fluid. An optimal designed of the MR clutch is then studied to find out the optimal geometric dimensions of the clutch that can transform a required torque with minimum mass. A prototype of the optimized MR clutch is then manufactured and its performance characteristics are experimental investigated. A DC motor speed control system featuring the optimized MR clutch is design and manufactured and a controller is then designed to control the output speed of the system. In order to evaluate the effectiveness of the proposed DC motor speed control system, experimental results of the system are obtained and presented with discussions.

9057-102

Optimal design of a jetting dispenser actuated by a dual piezoactuator

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This research work focuses on optimal design of a high frequency jetting dispenser dually actuated by a two piezoactuators. Firstly, a new configuration of the high frequency jetting dispenser for integrated circuits (ICs) fabricating is proposed. The optimal design of the jetting dispenser is then considered. In the optimal design, significant parts of the jetting dispenser such as the piezoactuators, the amplifying lever, return spring, the needle and the nozzle are considered. Firstly, the geometry of the nozzle and needle is optimally designed considering the maximum velocity of dispensed adhesive, the pressure and viscous force acting on the needle. The other significant parts of the jetting dispenser such as the piezoactuators, return spring and the amplifying lever are designed so that the dispenser has a compact size and can work well at 1000Hz. In order to evaluate the optimal results, simulated transient results of the system based on finite element analysis are obtained and presented.

9057-103

Effects of eccentricity and order of vibration modes on the inelastic seismic responses of 3D steel structures

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In torsionally coupled buildings, the total response of the structure is the result of the translational displacement of the story's center of stiffness and the displacement due to the roof's rotation. In structures with high eccentricity, the effect of the floor's rotation in the total response is considerable. The order of vibration modes is another important parameter that changes the contribution of the different translational and rotational modes in the total response of the structure. To explore the effects of eccentricity and the order of vibration modes on the total response, a number of 3-D steel moment-resistant frames with 4, 8, and 12 stories, with different eccentricities and plans, were considered. The structures were subjected to bi-directional seismic inputs so that their pick ground accelerations were scaled to 0.4g, 0.6g, and 0.8g. Increasing the eccentricity of the structure increases the participation of rotation in the total response. Furthermore, in torsionally flexible structures, where the first or second mode of vibration is a torsional mode, the contribution of the floor's rotation can be even greater. In some cases, the displacement of exterior columns is primarily the result of the floor's rotation. This suggests that to efficiently dampen the seismic displacement of such structures, the rotational mode of the building should be controlled.

9057-104

An active vibration isolation system using adaptive proportional control method

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This paper is concerned with an six-degree-of-freedom active vibration isolation system using voice coil actuators with absolute velocity feedback control for highly sensitive measurement equipment, e.g. atomic force microscopes, suffering from building vibration. The main differences between this type of system and traditional isolator, is that there are no isolator resonance. The absolute vibration velocity signal acquired from an accelerator and being processed through an integrator is input to the controller as a feedback signal, and the controller output signal drives the voice coil actuator to produce a sky-hook damper force. In practice, the phase response of integrator at low frequency such as 2~6 Hz deviate from the 90 degree which is the exact phase difference between the vibration velocity and acceleration. Therefore, an adaptive filter is used to compensate the phase error in this paper. An analysis of this active vibration isolation system is presented, and model predictions are compared to experimental results. The results show that the proposed method significantly reduces transmissibility at resonance without the penalty of increased transmissibility at higher frequencies.

9057-105

Piezoelectric energy harvesting using a series synchronized switch technique

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The modelling of an alternative switching technique for piezoelectric energy harvesting is presented. The energy harvester based on piezoelectric elements is a promising method to scavenge ambient energy. Standard technique and improvement technique(Such as SSHI) are used in previous studies. However, these techniques are sensitive to load and should be tuned to obtain nice power output. This technique, called Series Synchronized Switch Harvesting(S3H), has a working window where power output is constant-like with any given load. This harvesting circuit contains piezoelectric elements, switch and load. It will not close until the piezovoltage reach its maximum. After a designed switching on time t0, the circuit is open again. The energy scavenging process happens when switch is closed.

Based on the linear movements assumption, the harvester structure is modelled as a "Mass-Spring-Damper" system. The analysis of S3H technique is taken with harmonic excitation. Then an analytical model of S3H is presented and discussed. The power output is constant-like at any given load value(R<2000 Ohm) in both constant displacement excitation condition and constant force excitation condition. In constant displacement excitation condition, power output is inversely proportional to switching on time; However, in constant force excitation condition, optimal switching on time exists. Although the optimal switching on time increases with coupling coefficient(k2Qm), it is about 0.2~0.3 times of excitation period. Compared with standard technique, S3H may increase power 2.5 times at low k2Qm condition and perform same level(or a little advance) as standard technique does at high k2Qm condition.

9057-106

An enhanced knee-mounted biomechanical energy harvester

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Energy is becoming the major limiting issue for many portable devices. During activities, human body generates significant amount of biomechanical energy, which can be harvested by a wearable energy harvester. This energy harvester provides an alternative solution for powering portable devices such as prosthetic limbs. In this paper, a knee-mounted energy harvester with enhanced efficiency and safety is developed to convert the mechanical power into electricity during human motion. This developed device can change bi-directional knee input into uni-directional rotation for an electromagnetic generator by a specially designed gear transmission system. In the system, two one-way bearings are oriented in the opposite direction to selectively transmit the input torque from different rotating direction through different gear combination, and unify the final rotating direction at the generator. Therefore, all negative work during gait cycle can be utilized. Compared with the previous one-directional energy harvester, which only utilizes part of the negative work, the efficiency of energy harvesting is improved. This device also consists of a movable chute at the shaft, to allow about 20 degree of rotational freedom during walking, while assisting the power harvesting from the knee only when the muscles are doing negative work, to reduce the wearer‘s effort.

9057-107

Vibration control of shell-like structures with optical strain gauges

Simone Cinquemani, Francesco Braghin, Gabriele Cazzulani, Politecnico di Milano (Italy)

Carbon fiber structures are claimed to offer several advantages such as contained mass and high stiffness. However, these structures are characterized by a very low mechanical damping and, therefore, they are easily subjected to potentially dangerous vibratory phenomenon. Active control techniques have been widely developed to suppress vibration and great progresses have been achieved. On the other hand the research on sensors and actuators to be used is still a research field of interest. The paper discusses the opportunity to use piezoelectric actuators (PZT) and Fiber Bragg Grating sensors (FBGs) to realize a smart structure including in itself both the sensing and the actuating devices. Fiber optic strain sensors, such as Fiber Bragg Gratings (FBG), have a great potential in the use in smart structures thanks to their small transversal size and the possibility to make an array of many sensors. They can be embedded in carbon fiber structures and their effect on the structure is nearly negligible. Such a structure is able to measure its state of excitation and to reduce the amplitude of vibration using the embedded actuators.

Different control strategies have been implemented on a test rig consisting on a plate made of carbon fiber using two chains with 15 FBG sensors each and 6 PZT actuators. Control forces are designed to increase the damping of the structures, allowing to increase of damping of the first modes of vibration of about 10 times.

9057-108

Microthermogenerator with semiconductor oxides thermoelectric materials

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In thermoelectric generators, the Seebeck effect is used for direct conversion of heat waste into an electric potential obtained between a pair junction of two materials, the thermocouple being subjected to a temperature difference. The most promising thermoelectric materials consist of n-type semiconductor $Ca_{0.9}La_{0.1}MnO_3$ with perovskite structure and p-type semiconductor $Ca_3Co_4O_9$ with misfit layered structure. The thermoelectric properties were tested using a microthermogenerator with one module constituted from a pair of $Ca_{0.9}La_{0.1}MnO_3$ and $Ca_3Co_4O_9$ synthesized by sol gel method. The microthermogenerator module consists of thermoelectric materials in

cylindrical form with dimensions: ?4 mm x 2.25 mm inserted in a PCB substrate. The substrate is made of FR-4 printed circuit board laminate. The conductive layers were drawn with conductive silver paint and deposed above the thermo-legs with a metallic pen. The performance of thermoelectric materials was evaluated using the dimensionless figure-of-merit: ZT=?2T/? k, where, ?, T, ?, k, are the Seebeck coefficient, the electrical conductivity, the absolute temperature, electrical resistivity and thermal conductivity. The electrical resistivity was measured with Van der Pauw method were: 2.56x10-4 Ωm for Ca0.9La0.1MnO3 and 1.26x10-4 Ωm for Ca3Co4O9 at 298K. The thermal conductivity was determined by flash method for both materials and the valus obtained were: 1.641 W/mK at 298K and 1.429 W/mK at 518K for Ca0.9La0.1MnO3 and 0.20 W/mK at 298K and 0.16 W/mK at 518K for Ca3Co4O9,. The thermoelectric parameters determined were: Seebeck coefficient of the module 350 ?V/K, figure-of-merit ZT 0.05, conversion efficiency 3%, voltage (U) 10.6 mV and power (P) 6.3 ?W for a temperature difference of 30K. The use of these materials in smaller modules together with module serialization for increased voltage can ensure the power supply for small power consumption electronics such as electronic watches or distributed wireless networks.

9057-109

Optimized shape of piezoelectric actuators for maximum coupling

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Mechanical vibrations in machines are mostly unwanted, as they reduce precision, increase wear and may lead to unwanted sound emission, e. g. brake squeal. Therefore, vibration damping remains a very important task for engineers. Beside passive damping techniques, active and semi-active systems become more and more relevant. Many of these systems use piezoceramics as sensors and actuators, because they are well suited for vibrations with frequencies in the audible range.

For a maximum performance of these actuators, the shape of the piezoelectric transducers and placement within the structure must be optimized. The generalized piezoelectric coupling coefficient can be used as a criterion. It measures the ratio of converted and stored energy of the piezoceramics.

This publication presents an in-depth analysis of the coupling coefficient for different types of piezoelectric actuators. Stack-actuators and different bending actuators are discussed. Beside a bimorph with two oppositely polarized piezoelements, a piezoelectric layer with substrate layer and two piezoelectric layers with one substrate layer inbetween are analyzed. The inhomogeneous strain and stress distribution within the piezoceramics and the substrate layer is calculated, and based on the energies the coupling coefficient is obtained. These results allow the optimization of the actuator geometry. Based on this, different realizations can be compared with each other, and the best suited solution be found.

9057-110

Numerical analysis of cyclical performance of RC beam-column connection reinforced by superelastic shape memory alloy bars

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Superelastic shape memory alloys (SMAs) are unique materials, possessing the ability to undergo large deformations, while returning to their original undeformed shape by the removal of stresses. The goal of this study is to assess the seismic behavior of RC beam-column connections reinforced by SMA bars under reversed cyclic loading using finite element method (FEM). Based on FEM software, two simplified models of RC beam-column connections, one being reinforced with superelastic SMA bars and the other with regular steel bars, were established. The behavior of the two models, including deformation capacity and energy dissipation, under reversed cyclic loading are compared. Moreover, the lengths of plastic hinge and load-displacement relationship as well as moment-rotation curves are preliminarily investigated. The numerical results show that the concrete beam-column connections reinforced by SMA bars can not only experience large inelastic deformations, but recover most of its post-yield deformation. And it also shows the promise of the application of SMA bars in increasing the seismic property of concrete beam-column connections.

9057-111

Superelastic viscous dampers for seismically resilient steel frame structures

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This study proposes a passive control device based on superelastic behavior of shape memory alloys (SMAs) and investigates the device performance for improving response of steel frame structures subjected to multi-level seismic hazards. The device, named as Superelastic Viscous Damper (SVD), exhibits both re-centering and energy-dissipating capabilities and consists of SMA bars and a viscoelastic (VE) damper. SMA elements are mainly used as re-centering unit and the viscoelastic damper is employed as energy dissipation unit. The VE damper consists of two layers of VE material bonded with steel plates. Energy is dissipated through the shear deformation of VE material. Two baffle plates that can move inside the device enclosure are attached at both ends of VE damper. A total of 8 groups of SMA elements are fixed on the baffle plates by clamps.

An analytical model of a three-story benchmark steel building with the installed SVDs is developed to determine the response of the structure under a ground motion input. A neuro-fuzzy model is used to capture rate- and temperature-dependent nonlinear behavior of the SMA elements of the SVD. Incremental dynamic analyses are conducted at different intensity levels. A suite of ten ground motion records is employed in nonlinear response time history analysis. Peak interstory drift, peak floor acceleration, and residual story drift are selected as the primary demand parameters. Results shows that SVDs can effectively mitigate dynamic response of steel frame structures under strong ground motions and enhance their post-earthquake functionality.

9057-112

Semi-active controller design for vibration suppression and energy harvesting via LMI approach

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The vibration control plays an important role in energy harvesting systems. Compared to the active control, semi-active control is a more preferred alternative for practical use. Many different semi-active control strategies have been developed, among which LQ-clip, Skyhook and model predictive control are the most popular strategies in literature. In this paper, a different control strategy that design semi-active controller via LMI approach is proposed. Different from saturating the control input after controller construction, the proposed controller fulfill the semi-active control input feasibility constraints before the controller construction. The methodology is developed through LMI approach which leads to a stabilizing linear controller to ensure semi-active constraint and the pre-designed robust performance minimizing the H_2 norm of the transfer function from exogenous input to controlled output. The new method formulates the semi active actuator constraint and optimizing problem as a standard LMI problem in 3 variables. The variable elimination lemma and Finsler's lemma have been used in design to convert the original BMI constraints to LMI constraints which can be solved by standard convex optimization method. Since the LMI approach is used, the proposed methodology significantly increases the flexibility of controller design in which any other control requirements and restrictions can be seen as additional LMI constraints added into current LMI problem. The proposed design is illustrated by a single actuator Tuned Mass Damper (4th order TMD) system which is widely used in tall building vibration control and energy harvesting. The paper also furthers the proposed controller to multi-actuator semi-active control systems in which the efficiency of the proposed controller will be shown.

9057-113

Shock and vibration control systems using a self-sensing magnetorheological damper

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The theoretical analysis and the prototype testing of the integrated relative displacement self-sensing magnetorheological damper (IRDSMRD) indicate that the controllable damping performance and the relative displacement sensing performance influences each other for varying applied currents. Aiming at verifying the feasibility and capability of the IRDSMRD to semi-active shock and vibration control systems, this study presents the control performance of a single-degree-of-freedom (SDOF) shock and vibration control system based on the IRDSMRD. The mathematical model of the IRDSMRD, including the damping force and the linearity of the integrated relative displacement sensor (IRDS), is established, and the governing equation for the SDOF system based on the IRDSMRD is derived. A skyhook control algorithm is utilized to improve the shock and vibration control performance of the systems. The simulated control performance of the SDOF control systems using the IRDSMRD without extra-set dynamic sensor, conventional MR damper with a linear variable differential transformer (LVDT), and passive damper, under shock loads due to vertical pulses (the initial velocity is as high as 10 m/s), and sinusoidal vibrations, are evaluated, compared, and analyzed.

9057-114

An adaptive optimal control for smart structures based on the subspace tracking identification technique

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In order to reduce the vibrations in light and flexible structures, during the last years many active control strategies have been developed. Among the other techniques, adaptive active controls represent a particularly attractive solution for nonlinear and time-varying systems. A new method for the real-time identification of mechanical system parameters is presented in this paper. An ARMA model processes the signal previously decomposed by the Subspace Tracking and a statistical approach is applied to estimate the system natural frequencies and damping ratios and to collect information about the unknown external disturbance. Indeed, thanks to the identification of the disturbance frequency and the most excited modes, it is possible to choose the optimal gain matrix for the model-based controller in order to minimize the vibrations and the control forces. Two different approaches are used for the control synthesis. The former is an adaptive LQR control solving the algebraic Riccati equation starting from the identified state space matrix A. The latter is a standard gain scheduling control. The control scheme is completed by an optimal state space observer. The "identification and control" algorithm is experimentally tested on a carbon fiber plate smart structure. It is actuated by three piezoelectric patches and it is instrumented with three accelerometers and three strain gages. Indeed, besides the real time identification needing only one sensor, the other inputs are acquired for the state space observer.

9057-115

Eliminating whirl occurrence in fluid-film bearings of rotary machinery through optimally controlled anti-swirl injection

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The phenomenon of fluid-induced instability existing in fluid-film bearing systems has been coped with for long time. The study aims to soothe and even eliminate the occurrence of whirl in rotary machinery by increasing the threshold of instability through the anti-swirl injection using an optimal control based linear quadratic regulator. An acceptance region was established in order to decide starting up the control process. Some case studies were carried out to illustrate the effectiveness of the control scheme. The research results present that a simple control method incorporating with an acceptance region enables to avoid the fluid induced instability flexibly in rotary machinery. Moreover, the developed techniques can also be applied in other fluid-induced instability problems such as whip and rub, etc.

9057-116

Appropriate IMFs associated with cepstrum and envelope analysis for ball-bearing fault diagnosis

Min-Chun Pan, Wen-Chang Tsao, National Central Univ. (Taiwan)

The traditional envelope analysis is an effective method for the fault detection of rolling bearings. However, all the resonant frequency bands must be examined during the bearing-fault detection process. To ameliorate the above deficiency, this paper presents a new concept based on the empirical mode decomposition (EMD) to choose an appropriate intrinsic mode function (IMF) for the subsequent envelope analysis and cepstrum analysis. By virtue of the band-pass filtering nature of EMD, the resonant frequency bands of structure to be measured are captured in the IMFs. As impulses arising from rolling elements striking bearing faults modulate with structure resonance, appropriate IMFs are potentially able to characterize fault signatures, instead of always using IMF 1. In the study, single- and dual-fault bearings are used to justify the proposed method, and comparisons with the traditional envelope analysis are made. Post the selection of IMFs, the performance of using envelope analysis and cepstrum analysis to single out bearing faults is objectively compared and addressed.

9057-117

Analysis of the robust stability of piezoelectric shunt damping system with synthetic negative capacitor

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The piezoelectric shunt damping is a technique for sensor-less damping with electromechanical transduction of piezoelectric material. The performance of damping depends on the shunt circuit attached to the terminals of piezoelectric material.

There exist many implementations of the shunt circuit. Synthetic

impedance or synthetic admittance can simulate any circuits with a computer and software, therefore is expected for advanced shunt damping method. As the current source of virtual admittance, a current amplifier is commonly used. However, a charge amplifier is much less used.

In this paper, we developed a grounded charge amplifier for the synthetic admittance. We show that the synthetic admittance using a grounded charge amplifier is superior to that using a current amplifier for two reasons. One is that the synthetic admittance with a charge amplifier achieves the drift compensation by itself in many cases. The other is that the order of the denominator of transfer function increases to lead highly flexible design of admittance compared with one using a current amplifier.

We simulate a negative capacitor circuit with the developed synthetic admittance. We also discovered that a negative capacitor circuit may lead to instability of the system owing to the perturbation of the electrical system. In order to avoid the instability of the system caused by the perturbation, analysis of the robust stability of the system with the negative capacitor circuit is shown. The experimental result demonstrates the validity of the developed circuit and the effectiveness of the proposed stable design of the negative capacitor.

9057-119

Theoretical and experimental analysis of frequency up-conversion energy harvesters under human-generated vibrations

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Piezoelectric energy harvesters are devices capable of converting the kinetic energy present in vibration-based motion into electrical energy using piezoelectric transducers. This kind of device has its maximum efficiency when the exciting frequency matches its natural frequency. In the past years, some authors have explored the use of human motion as a vibration source, and harvesting energy in this situation is not trivial because the low-frequency characteristics of the motion are not compatible with small, light-weight transducers, which have high natural frequencies. To overcome this problem, a method known as frequency up-conversion is used; it consists of a nonlinear vibration-based, magnetically excited harvester that exhibits frequency-independent performance, allowing the device to be efficient in a wide band of frequencies. In this work, the power output of a piezoelectric energy harvesting with frequency up-conversion submitted to walking and running vibrations is analyzed.

Data are collected using an accelerometer located on the front pocket of each subject and then used in simulations. The model used consists of a cantilever beam with a magnetic tip at the free end; this tip interacts with a magnetic structure that adds nonlinearities to the model. A pure resistance matching the device's impedance at its fundamental frequency is used to account for the output power. To verify the advantages of using the frequency up-conversion method for vibration-based energy harvesters regarding the power output and frequency band, a comparison with the linear cantilever model is analyzed. Also, in order to confirm the simulation results, a prototype of the device is built and submitted to vibration tests using a vertically oriented vibration exciter that recreates the motions recorded by the accelerometer; it will be tested with and without the magnets in order to experimentally determine the nonlinearities' effects on the power harvesting performance. Finally, a charging circuit will be attached to the energy harvester to verify the capability of the frequency up-conversion to charge a battery.

9057-120

One-step Fabrication of Multifunctional Silica Microbelt with the Novel Stacked Structure by Electrospinning Technique

Yongtao Yao, Weilong Yin, Harbin Institute of Technology (China)

The flexible trailing-edge actuated by pneumatic muscles is developed from the viewpoint of bionics in this paper. The alternate contraction of pneumatic muscles located on the upper and lower surface makes the deformed wing surface smooth, Continuous and Seamless. The pneumatic muscle with the outer diameter of 4mm is developed. The experimental results show that the maximum output force of pneumatic muscles fibers with the diameter of 4mm is 27N when the air pressure is 0.4MPa and the maximum contraction ratio can reach 26.8%. The mechanical model of the flexible trailing-edge actuated by pneumatic muscles is developed by use of deformation theory of the elastic beam. The effect of the bending deformation on the axial displacement is considered. The numerical results show that the deflection angle of the flexible trailing-edge can be controlled by adjusting the pressure of the pneumatic muscle. The deflection angle of the steel plate with the thickness of 0.6mm can be up to 20° when the pressure of the pneumatic muscle is 0.3MPa.

9057-121

Solar self-tracking system powered by shape memory alloy wire

The Minh Nguyen, Giridharan Rajagopalan, Tejaswini Lakkaraju, Alhasan Almakarami, California State Univ., Fresno (United States)

No Abstract Available

9057-122

Shape memory alloy-based active chiral composite cells

Maulik Prajapati, D. Roy Mahapatra, Indian Institute of Science (India)

A morphing structural element is studied which has its origin in well known chiral honeycomb composites. The new aspect of design and functionality explored in this paper is that the chiral cell is actuated using a family of thermal Shape Memory Alloy (SMA) actuator wires to provide directional motion. As a result of this actuation by thermoelectric effect, which is anyway needed to realize the chiral deformation function, there is a great amount of nonlinear geometric and material interactions within the cell. The stiffness and in-plane compliance of the cell need to be designed optimally so as to sustain applied mechanical load which achieving the chiral effect in deformation under combined effect of external force and internal actuation force. Chiral topological constructs are obtained by considering passive and active load path decoupling and sub-optimal shape changes. Single chiral cells with actuator is analyzed using finite element simulation results and experiments. To this end, a multi-cell planform is characterized showing interesting possibilities in active structural morphing applications. The applicability of the developed chiral cell to flexible wing skin, variable stiffness based design and controlling longitudinal-to-transverse stiffness ratio are discussed.

9057-123

Theoretical and experimental investigation of architected core materials incorporating negative stiffness elements

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Structural assemblies incorporating negative stiffness elements have been shown to provide both tunable damping properties and simultaneous high stiffness and damping over prescribed displacement regions. In this paper we explore the design space for negative stiffness based assemblies using analytical modeling combined with finite element analysis. A simplified spring model demonstrates the potential to provide controlled high damping and stiffness performance through the tailoring of design parameters including element stiffness, geometric configurations, and the preloads. The simplified analytical results were validated for realistic structural implementations through finite element analysis. A series of complementary experiments was conducted to compare with modeling and determine the effects of each element on the system response. The measured damping performance matches the theoretical predictions obtained by both analytical and finite element analysis with an error of less 5%. We applied these concepts to a prototype sandwich core structure that exhibited novel damping and stiffness properties compared to existing core approaches such as closed cell foams. The combined stiffness and damping properties of these prototype systems exhibited an enhancement of 2x over existing core technologies.

9057-124

Development of a biologically inspired hydrobot tail

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It has been hypothesized that Europa, one of the moons of Jupiter, has a large ocean underneath a thick layer of ice. In order to determine whether life exists, it has been proposed that an underwater glider (hydrobot) capable of propulsion could be sent to explore the vast ocean. In this research, we considered smart materials to create a propulsion device inspired by dolphin tails. Dolphins are highly efficient and excellent gliders, which makes them the ideal candidate for ocean exploration. In order to select the best dolphin species, we began by reviewing literature and then utilized the Analytical Hierarchy Process (AHP) to compare the different species. Lagenorhynchus obliquidens (Pacific White-Sided Dolphin) was found to be the best choice for creating a bio-inspired hydrobot. We then conducted literature review of various smart materials and using this knowledge constructed a hydrobot tail prototype. This prototype demonstrates that smart materials can be fashioned into suitable actuators to control a tail fashioned after a dolphin.

9057-125

The influence of osmotic pressure on the lifespan of cellularly inspired energy-relevant materials

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Bimolecular unit cells, formed through the droplet interface bilayer (DIB) technique, have recently become a focus for biologically-inspired smart materials. This is largely due their ability to exhibit many of the same properties of the natural cell membrane. In this study, two lipid monolayers formed at a water/oil interface are brought together, creating a lipid bilayer at their interface with each droplet containing a different concentration of ions. This ionic concentration gradient leads to the development of a membrane potential across the bilayer as ions begin to passively diffuse across the membrane at varying rates, providing the proof of concept for energy storage through cellular mechanics.. The focus of the study is to determine the influence of osmotic pressure on the lifespan of the lipid bilayer. We hypothesize that the greater osmotic pressure that develops from a greater ionic concentration gradient will prove to have a negative impact on the lifespan of the bilayer membrane, causing it to rupture sooner. This is due to the substantial amount of osmotic swelling that will occur to compensate for the ionic concentration gradient. This study will demonstrate how osmotic pressure will continue to be a limiting factor in the effectiveness and stability of cellularly-inspired energy relevant materials.

9057-126

Tapered two-layer stacked vibration energy harvesters using a modal approach

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Two-layer stacked piezoelectric vibration energy harvesters (VEHs) using convergent and divergent tapered structures have been developed for broadband power output. A base cantilevered beam is bounded with an upper beam by a spacer to develop a Zigzag configuration. Two masses are attached to each layer to tune the resonsnace frequencies of VEH and one of these masses also serves as a spacer. By varying the positions of the masses, the VEH can generate close resonance frequencies and considerable power output in the first two modes. A modal approach is introduced to determine the modal performance using mass ratio and modal electromechanical coupling coefficient. Mass ratio represents the influence of modal mechanical behaviour on the power density directly. The required modal parameters are derived using the finite element method. Since the dominant mode with too large mass ratio causes the remaining modes to have smaller mass ratios and lower power densities, a screening process is developed using the modal approach to pre-select the VEH configurations with close resonances and favourable values of mass ratio before carrying out full analysis. The performances of VEHs using tapered beams are compared with VEHs using rectangular beams in both mechanical and electrical domains.

9057-127

Doormat-like energy harvester from footsteps: design, modeling and experimental analysis

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This paper presents the design, modeling and experimental analysis of a doormat--?liker energy harvester. With the unique design of amplified piezoelectric stack harvester, (APSH), the kinetic energy generated by footsteps can be effectively captured and converted into usable DC power that could potentially be used to power many electric devices, such as smart phones, laptops, sensors, monitoring cameras, etc. This doormat--?like energy harvester can also be used in the entrances of heavily used city public transportation facilities, such as subway station entrances, subway train/city bus door steps, airport escalator/elevator/

stairs entrances, or underneath the dancing floors in any city center. The harvested energy provides an alternative power supply for lighting, light--?up street signs, or light--?up advertisements, in order to reduce power requirement from the grid, which is always supplied by power stations that runs on highly polluting, global--?warming--? inducing fossil fuels. Therefore, this proposed doormat--?like portable energy harvester is believed to be energy efficient and environment sustainable. In this paper, two modeling approaches are compared to calculate power output. The first method is derived from the single degree of freedom constitutive equations, and then a correction factor is applied onto the resulting electromechanically coupled equations of motion. The second approach is deriving the coupled equations of motion with Hamilton's principle and the constitutive equations, and then formulating it with the finite element method. Experiments testing results are presented to validate modeling approaches.

9057-128

Angular placement of turbines over moving train to generate drag free electricity

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Trains generate large quantities of untapped energy which can be used for the generation of electricity. This electricity generated might not only reduce the amounts of energy being used by railways but also can reduce the burden on the energy grid. Some of the successful models which showed promising and effective results were, Qian Jiang & Ale Leonetti Luparini designed the "T-Box" [1]. The T-Box is to be installed within the actual railing track itself. The wind moving opposite to the train moves the turbines embedded in the railing track. Kartik Kumar proposed a mini wind turbine on the train that can harness high powers by utilizing the wind moving opposite to the moving train[2].

Sinhyung Cho, Hong Sun Hye and Ryu Chan Hyeon [3] have designed a concept to embed wind turbines perpendicular to the walls of the underground tunnels in order to utilize the high speed wind generated by passing subway trains. This concept was used by a student of Kalindi College at Delhi [4], who envisaged that the optimal positions for the turbines are at the entries and exits of the tunnel where the trains move from the underground to overhead lines. Santosh Pradhan[5] proved that wind pressure on a moving train cab be harnessed using a system of turbo-chargers and impellers mounted over the train where large quantities of compressed air is generated through them. This compressed air would then be directed into pressure tanks for storage, and can be used to rotate turbines fixed to a generator to produce electricity.

From previously researched modules, it is evident that, turbines play a major part in production of electricity. The major difference lies in the rotation and placement of these turbines. And the challenging part is the positioning of the turbines.

In this paper, Positioning has been evaluated in order to maximize the output power. Optimum results are expected when the axis of turbine is set at 90 degrees to the axis of train .In order to reduce the drag on the train, only half part of the turbine is exposed to wind . Opening both the halves of the turbine would result in a counter balance and would even stop the movement of the turbine. A three blade turbine is used for this project in order to reduce the extra load on the train while keeping the half air pass model intact. Net calculations based on the total power generated from a single turbine placed at different angular positions, excluding the drag imposed on the train were evaluated.

In concluding this paper, the major emphasis is made on maximizing the amount of electricity generated by the best possible positioning of the turbine over the train. Calculations were done with varying angular positions and varying radii of the turbine and the total amount of energy being generated verses the total drag force created was estimated.

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9057-129

Rate-dependent, flexible extensible smart device using shear thickening fluid

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A novel "dynamic ligament" smart material that exhibits a highly-discontinuous rate-dependent response is developed and characterized.

The devices, based on elastomeric polymers and shear thickening fluids, exhibit low resistance to extension at rates below 10 mm/s, but when stretched at 100 mm/s or higher resist with more than 10X higher force. A link between the shear thickening fluid's rheology and the dynamic ligament's tensile performance is presented to explain the rate-dependent response. Future recommendations for improving device performance are presented, along with a host of different potential application areas including safety equipment, adaptive braces, sporting goods, and military equipment.

9057-33a

Broadband energy harvesting via adaptive control of bistable potential energy separatrix

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As a result of the documented performance limitations of conventional linear piezoelectric energy harvesters, researchers have focused their efforts towards device designs that can better capture broadband energy. The approaches used can be classified into three categories: frequency tuning, multi-modal energy harvesting, and nonlinear energy harvesting. Of the nonlinear harvesting approaches studied, bistable energy harvesters have been shown to have the most robust performance when subjected to broadband harmonic & stochastic excitation. A conventional method for developing a nonlinear bistable restoring force is through use of magnetic repulsion. In these studies, a common theme of high-energy orbit breakdown occurs during a frequency upsweep. The issue at hand is the inability of the device inertial forces to overcome the potential energy barrier (separatrix) inherent to a bistable potential energy.

This paper proposes the use of a high-permeability electromagnet for adaptively controlling the bistable magnetic repulsion force to expand the frequency bandwidth for high-energy harmonic oscillations. Numerical simulations of the nonlinear oscillator are used to study the system response under varying parameters of separation distance and electromagnetic coil current. An analytical model of the magnetic moment of an electromagnet is developed for use in studying the force interaction between repulsing magnets and to determine the parametric space that generates buckling loads in a cantilever bimorph energy harvester.

9057-34a

On the snap-through dynamic characteristics for broadband energy harvesting with bi-stable composites

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Nonlinear systems have been shown to maintain large amplitude oscillations over a wider range of frequencies than their linear counter parts. In particular, systems exhibiting bi-stability have been shown to offer a significant bandwidth for high energy conversion. This is mainly due to the broadband nature of steady-state oscillations visiting both stable states, i.e. cross-well oscillations, which are physically realised by a dynamically triggered repeating snap-through action. Amongst the systems exhibiting such behaviour, bi-stable composite laminates show several advantages including: design flexibility for multiple resonance tuning owing to their two-dimensional nature, and reduced complexity realisation as no external devices (such as magnets) are required to achieve bi-stability. Encouraging results employing such structural systems have been obtained, yet the phenomena involving the dynamics of snap- through and their impact in the harvesting characteristics still deserve further detailed study.

In this paper, the relevant characteristics of dynamically triggered snap-through of piezoelectric bi-stable composite laminates are investigated. A nonlinear model for the dynamics of the bi-stable composites is used to study the relation between the frequency range for which dynamically triggered snap-through is observed with respect to the excitation parameters. Furthermore, the effect of the negative stiffness exhibited as the laminate experiences a snap-through on the energy harvesting characteristics of such systems is investigated. The obtained relationships provide a tool for designing the frequency range for which high energy conversion of bi-stable systems is obtained, aiding the design of harvesting devices based on such structural concepts.

9057-35a

Broadband and band-limited random vibration energy harvesting using a piezoelectric patch on a thin plate

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The literature of vibration-based energy harvesting has mostly focused on resonant cantilevered structures. However, cantilevered beam-type harvesters have limited broadband vibration energy harvesting capabilities unless they are combined with a nonlinear component. Moreover, cantilever arrangements cannot always be mounted on thin structures (which are basic components of marine, aerospace, and ground transportation systems) without significantly affecting the host system's design and overall dynamics. A patch-based piezoelectric energy harvester structurally integrated to a thin plate can be a proper alternative to using cantilevers for harvesting energy from thin structures. Furthermore, plate-like structures have more number of modes over a given frequency range, offering broadband performance characteristics. In this paper, analytical modeling and case studies of broadband and band-limited random vibration energy harvesting using a piezoceramic patch on a thin plate are presented. After validating the electromechanical frequency response functions experimentally, example cases are presented to investigate the expected power output of a piezoceramic patch attached on an aluminum plate with fully clamped boundary conditions. The effect of bandwidth of random excitation on the mean power and shunted mean-square vibration response are explored with a focus on the number of vibration modes covered in the frequency range of input power spectral density.

9057-36b

Performance analysis of a semi-active railway vehicle suspension featuring MR dampers

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The realization of high speed railway vehicle has been provided with efficient transportation including passenger and freight railway vehicles. However, the high speed railway vehicle would cause car body vibration which can induce the various problems such as ride stability, ride quality and track abrasion. In generally, to control the vibration, three types of suspension systems have been proposed: passive, active and semi-active. The passive suspension system provides simple design but have performance limitations. The active one provides high control performance in wide frequency range. However, it requires not only high power sources but also sophisticated control algorithm. On the other hand, the semi-active suspension system offers desirable performance without large power source and expansive hardware. So, recently various semi-active suspension systems featuring MR (magnetorheological) fluid have been studied and successfully applied in the real field, especially in wheel based passenger vehicle suspension system. This paper presents performance analysis of semi-active railway vehicle suspension system using MR fluid damper. In order to achieve this goal, dynamic model of railway vehicle is designed by mathematical model which contains car body, bogie frame and wheel-set able to represent lateral, yaw and roll motion. Based on this model, the dynamic range of MR damper at the railway secondary suspension system and design parameters of MR damper are calculated. Also, the control performance of railway vehicle including car body lateral motion and acceleration of MR damper is evaluated through the computer simulations. Then, the MR damper is manufactured to be retrofitted with the real railway vehicle and its characteristics are experimentally measured. Subsequently, the control performance of MR damper is assessed using test rig composed of a car body and two bogies.

9057-37b

Characterization and experimental validation of a squeeze film damper with MR fluid in a rotor-bearing system

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The general study and applications of Magneto-Rhelogical (MR) dampers have been spread in the lasts years, but only some studies have focused on the vibration problems of rotor-bearings systems. Squeeze-Film Dampers (SFD) are commonly used to passively control the vibration response on rotor-bearing systems because they can provide flexibility, damping and extend the so-called stability thresholds. More recently, SFD are combined with MR or Electro-Rheological (ER) fluids to introduce a control mechanism to modify the rotordynamic coefficients and deal with the robust performance of the overall system response for higher operating speeds. There are, however, some theoretical and technological problems that complicate their extensive use, like the relationship between the centering spring flexibility and the rheological behavior of the smart fluid to produce the SFD forces. In this work it is considered a SFD with MR fluid and a set of circular section beams in a squirrel cage configuration like centering springs. The mathematical model analysis includes the controllable viscoelastic properties associated to the MR fluid. The characterization of the SFD is made by the experimental determination of some coefficients associated with a modified Choi-Lee-Park polynomial model using a shaker to provide external excitation forces. During the analysis is considered a rotor-bearing system modeled using finite element methods. The SFD with MR fluid is connected to a platform with a small rotor-bearing system to validate and experimentally evaluate the overall system.

9057-38b

Study of a magnetically field-controllable phononic crystal

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(United States)

Phononic crystals are periodic structures consist of different materials in an elastic medium designed to interact with elastic waves. These crystals have practical applications, such as, frequency filters, beam splitters, sound or vibration protectors, acoustic lasers, acoustic mirrors and elastic waveguides. In this study, the wave propagation in a tunable phononic crystal for ultrasonic frequency range is investigated. The controllable phononic crystal consists of a magnetorheological soft (hyperelastic) medium undergoing large deformations upon the application of a magnetic field. Finite deformations and induced magnetic fields influence wave propagation characteristics in the periodic structure. The soft matrix is modeled as a hyperelastic elastomer to take into account the material nonlinearity. The integrated effects of material properties, transformation of the geometry of the unit cell, together with the induced magnetic field, are used to tune the band structure of the periodic structure. Both analytical and finite element methods are employed to evaluate the dispersion diagrams considering Bloch boundary conditions. Results show that various patterns of deformation and different levels of magnetic fields significantly affect the position of band-gaps and the cutoff frequencies.

9057-39a

Piezoelectric assisted smart satellite structure (PEASSS): an innovative low cost nano-satellite

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The PEASSS project includes new nano-satellite electronics, a piezo power generation system based on the pyroelectric effect, a piezo actuated smart structure, and a fiber-optic sensor and interrogator system. The designs are going to be prototyped into breadboard models for functional development and testing. Following completion of operational breadboards, components will evolve to flight-test ready hardware and related software, ready to be integrated into a working satellite. Once the nanosatellite is assembled, ground tests will be performed. Finally, the satellite will be launched and tested in space at the end of 2015.

The present manuscript describes the various modules of the nanosatellite, their predicted performance based on both calculations and tests and highlights the new innovative technology.

The piezo actuated structure, the first module, consists of two piezoelectric bimorphs aimed at tilting an optical sun sensor located on a gimbal at ±2.50. The use of piezoelectric actuators is expected to increase the pointing accuracy and thermal stability of the optical benches, while saving mass and power. The authority of the bimorphs to tilt the optical bench was tested and compared to theoretical predicted results yielding a good correlation between the two.

The second module consists of a fiber optic system (FBG (Fiber Bragg Gratings) + interrogator) aimed at measuring the strain due to the bending of the bimorphs, and controlling their performance.

The next module consists of a power generator, containing piezoelectric thin plates wrapped in epoxy to sustain the loads during launch. The piezo-pyroelectric effect will be used to transform the thermal energy into electrical energy. The time variation of the temperature caused by the spinning of the satellite will be the source of variable thermal energy, thus enabling the use of the pyroelectric effect. . Preliminary terrestrial tests predict a promising power per volume of 5.82 mW/cm3 for temperature amplitude of 20oC, and a frequency of 0.05 Hz.

Innovative nanosatellite electronics consisting of next generation computer, data handling and power supply form the last module. This next generation electronics for small satellites will be space qualified yielding a further advancement in the field.

9057-40a

Design, characterization, and testing of macro-fiber composite actuators for integration on a fixed-wing UAV

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Smart materials offer several potential advantages for UAV flight control applications compared to traditional servo actuators. One important benefit is that smart materials are lightweight and can be embedded directly into the structure of a wing or control surface. Therefore, they can reduce the overall weight of the vehicle and eliminate the need for mechanical appendages that may compromise the form factor of the wing, benefits that become more significant as the size of the vehicle decreases. In addition, smart materials can be used to realize continuous camber change of aerodynamic surfaces. Such designs offer improved aerodynamic efficiency compared to the discontinuous deflections of traditional hinged control surfaces driven by servoactuators. In the research discussed in this paper, macro-fiber composite (MFC) aileron actuators will be designed for implementation on a medium-scale, fixed-wing UAV in order to achieve roll control. Macro-fiber composites, which consist of piezoceramic fibers and electrodes embedded in an epoxy matrix, are an attractive choice for UAV actuation because they are manufactured as lightweight, thin sheets and, when implemented as bending actuators, can provide both large structural deflections and high bandwidth. In this study, several MFC actuator designs will be developed, constructed, and tested for integration on a UAV as aileron actuators. Bench tests will be conducted to measure the voltage-deflection relationship for each design in addition to the bandwidth, weight, cost, and power requirements. Further testing will be performed in a wind tunnel to assess the effect of aerodynamic loading on the performance of each actuator design. Bench and wind tunnel test results will be used to develop MFC actuator models, which will be used for simulation studies and also as a design tool for future studies. Finally, the MFC actuators will be integrated on a UAV, and open-loop flight tests will be performed in which the UAV is controlled by an RC pilot. The performance and handling qualities of the MFC-actuated UAV will be compared to that of a servo-actuated UAV. The results of this study will lead to future research extensions such as the use of MFC actuators in closed-loop UAV control systems as well as more complex designs such as morphing wing MAVs.

9057-41a

Aeroelastic performance evaluation of flexure box morphing airfoil concept

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Recent advances in smart material actuators, stretchable skin, and compliant structures have allowed for morphing airfoil designs that selectively tailor compliance to result in improved actuation. Using these advances and further refining the Flexure-Box morphing aileron concept, this work seeks to evaluate the impact on performance of MFCs in two different configurations: unimorph and bimorph. Implemented in a NACA 0012 airfoil, the performance of the Flexure Box aileron with unimorph and bimorph actuators is experimentally tested over a range of flow speeds up to 25 m/s and angles of attack ranging from -25 to 25 degrees in the University of Michigan 2'x2' wind tunnel. For both design choices, the effect of actuation on lift, drag and pitching moment coefficients is evaluated for both static and dynamic actuation, showing the ability of each to affect the flow considering blocking force. A combination of laser displacement sensor and calibrated embedded piezoresistive flex sensors are used to evaluate the effect of aerodynamic loading on tip position. Finally, the impact on aileron mass and electronics due to the added MFCs is considered. A shunt resistor is used to monitor the power consumption of a compact high voltage bimorph amplifier, for both the static and dynamic actuation cases. The resultant analysis provides a summary of the performance of the Flexure Box concept using unimorphs and bimorphs over a range of flight conditions and provides a comparison against conventional servo actuators in literature.

9057-42a

Variable stiffness cellular structures using pneumatic artificial muscles

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A recent work by Pontecorvo et al. [1] proposed a framework in which pin-jointed hexagonal unit cells can be supported internally by a variety of passive inclusions – such as springs [1], buckling beams [2], or dampers [3] – in order to tailor the in-plane behavior of the cells to specific applications. It was found that three inclusions between the vertices were necessary for the cell to be statically determinate. In the case of linear spring inclusions, expressions for the modulus of the cell in the vertical and horizontal directions were derived based on the stiffness of the springs.

This work builds on the concept proposed by Pontecorvo et al. by including pneumatic artificial muscles (PAMs) as nonlinear, semi-active, variable stiffness springs within the unit cell. PAMs are compliant pneumatic actuators with high force to weight ratios that are composed of an elastomeric bladder inside a braided mesh sleeve. Increasing the air pressure inside the actuator causes the actuator to expand radially and shorten axially, while also increasing the tensile stiffness of the actuator. Due to the asymptotic nature of the axial contraction, it is demonstrated that at pressures between 620 and 2069 kPa, the tensile stiffness of the actuator can change by a factor of 3 for only a 2.5% change in actuator length. As a result, the PAMs can be utilized in the pin-jointed hexagonal cell as variable stiffness springs, without appreciably changing the shape of the cell.

This paper details the design of three 6.35 mm diameter PAMs and their implementation as variable stiffness elements within a pin-jointed hexagonal unit cell. An analytical model of the PAMs is described and combined with expressions for the modulus of the cell to predict the modulus of the prototype based on the pressure within the PAMs. These predictions are then compared with measurements of the unit cell modulus taken with a tensile testing machine. It is concluded that the inclusion of the PAMs within the unit cell creates a repeatable, structural element whose stiffness in the vertical and horizontal directions can be varied by over a factor of 3 with little change in the shape of the unit cell.

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9057-43b

Inducing nonlinear structural dynamic response via piezoelectric circuitry integration

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Owning to the two-way electro-mechanical coupling characteristics, piezoelectric transducers have been widely used as sensors and actuators in sensing and control applications. In this research, we explore the integration of piezoelectric transducer with the structure, in which the transducer is connected with a nonlinear circuitry. It is shown that a type of current-feedback circuit with properly designed feedback function can induce considerable nonlinear effect in the structural dynamic response. Such integration has the potential to significantly amplify the response change when the underlying structure is subject to property change. In other words, when this scheme is employed for damage detection purpose, the sensitivity of the detection scheme can be enhanced remarkably. . Comprehensive analytical and experimental studies are carried out to demonstrate the concept and validate the performance improvement.

9057-44b

Design and simulation of PZT-based MEMS piezoelectric sensors

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Devices with increased sensitivities are needed for various applications including the detection of chemical and biological agents. This paper presents the design of microelectromechanical systems (MEMS) devices that incorporate lead zirconate titanate (PZT) films in order to realize highly sensitive sensors. In this work, the piezoelectric properties of the PZT are exploited to produce sensors that perform optimally for mass sensing applications. The sensor is designed to operate as a thin-film bulk acoustic resonator (TFBAR) whereas a piezoelectric is sandwiched between electrodes and senses a change in mass by measuring a change in resonance frequency. Modeling of the TFBAR sensor, using finite element analysis software COMSOL, was performed to examine optimal device design parameters and is presented in this paper. The effect of the PZT thickness on device resonance is also presented. The piezoelectric properties of the PZT is based on its crystal structure, therefore, optimization of the PZT film growth parameters is also described in this work. A detailed description of the fabrication process flow developed based on the optimization of the device design and film growth is also given. The TFBAR sensor consists of 150 nm of PZT, 150nm of silicon dioxide, the silicon substrate, titanium/platinum bottom electrodes, and aluminum top electrodes. The top electrodes are segmented to increase the sensitivity of the sensor. The resonance frequency of the device is 3.2 GHz.

9057-45b

Vibration characteristics of a discal piezoelectric transducer with spiral interdigitated electrodes

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Torsional vibrations of circular tubes, rods, rings, and disks are widely used as operation modes of acoustic wave transducers in various piezoelectric devices, such as ultrasonic motors, angular accelerometers, optical scanners, energy harvesters, and fluid sensors. They are especially suitable for fluid viscosity sensing in which the surface tangential vibrations produce fluid shear waves only, without generating complex compression waves in the fluid. While structural torsion is the macroscopic integration of local shear, conventional torsional piezoelectric elements adopt the shear piezoelectric d15 effect, but accompanying with inevitable driving and poling problems. Alternatively, piezoelectric tubes and fibers with helical electrodes are validated to generate torsional vibrations with d33 and d31 effects in a simple and effective manner. In this paper, a piezoelectric disk is proposed to generate in-plane torsion, in which spiral interdigitated electrodes are designed from the inspiration of helical electrodes. Vibration characteristics of the discal transducer are studied theoretically and experimentally. A simplified dynamic model is established to investigate the properties of torsional vibration accompanying with radial and tangential vibrations. Resonant frequencies and mode shapes with different boundary conditions are investigated. The trends of resonant frequencies as functions of several structural parameters are discussed and validated experimentally.

9057-46b

Experimental studies of a piezoelectric micropump using piezoelectric valves with annular boundary

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Micropumps are the core control elements and the essential components in microfluidic systems, and have great potential applications in lab-on-a-chips, drug delivery systems, liquid cooling systems, and insulin therapy systems. This article describes a normally closed piezoelectric-driven microfluidic pump with high accuracy control ability. In the proposed microfluidic pump, two microfluidic active controlled valves with annular boundary are used as fluid channel switches of the pump chamber, and results in the bidirectional controllable function of the microfluidic pump. Circular piezoelectric unimorph actuators act as the execution units of the microfluidic active control valves with annular boundary and the pump chamber. The circular piezoelectric unimorph actuators of the valves are in the same plane with that for the pump chamber and the valves chamber are also in the same plane with the pump chamber, so that the fabrication is simple. The prototype of the microfluidic pump is fabricated and the experimental setup is established. By changing the frequency, amplitude and phase relationship of the control signal of the circular piezoelectric unimorph actuators on the microfluidic active control valves with annular boundary and the pump, the flow rate and the output pressure of the microfluidic pump can be controlled accurately. The research in this paper provides a feasible solution to improve the pump flow control accuracy and achieve very low flow control. In addition, the proposed microfluidic pump can be fabricated by planar processing technology with low cost.

9057-47a

Modeling and enhancement of piezoelectric power extraction from one-dimensional bending waves

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Vibration-based energy harvesting has been heavily researched over the last decade to enable self-powered small electronic components for wireless applications in various disciplines ranging from biomedical to civil engineering. The existing research efforts in this interdisciplinary field have mostly focused on the harvesting of deterministic or stochastic vibrational energy available at a fixed position in space. Such an approach is convenient to design and employ linear and nonlinear vibration-based energy harvesters, such as base-excited cantilevers with piezoelectric laminates. However, persistent vibrations at a fixed frequency and spatial point, or standing wave patterns, are rather simplified representations of ambient vibrational energy. As an alternative to energy harvesting from spatially localized vibrations and standing wave patterns, this work presents an investigation into the harvesting of one-dimensional bending waves in infinite beams. The focus is placed on the use of piezoelectric patches bonded to a thin and long beam and employed to transform the incoming wave energy into usable electricity while minimizing the traveling waves reflected and transmitted from the harvester domain. To this end, wavelength matching, resistive-inductive circuits, and localized obstacles are explored. Electroelastic model predictions and performance enhancement efforts are validated experimentally for various case studies.

9057-48a

Finite element modeling of piezoelectric energy harvesters

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This talk reports a novel finite element (FE) modeling of piezoelectric energy harvesters accounting for the effect of rectified interface circuits. The idea is to replace the interface circuit together with piezoelectric capacitance by an equivalent load impedance. The latter can be easily implemented into the conventional FE solver. This approach offers several advantages at many aspects. First, it directly provides designing energy harvester devices on the whole without resorting to circuit solvers. There is no longer necessary applying FE simulation to identify equivalent parameters used in the circuit simulations. Second, the matching between the source and load impedances leads to deriving the electrically induced damping for different interface circuits. This gives key criterions for optimal power design. Third, the extensions to complicated structures such as array configurations are straightforward. The results are validated by the comparisons to those based on the coupled FE and SPICE simulations. Finally, it is remarkably found that power boosting based on array configurations remains hold even for large deviations in material parameters of each oscillator. In addition, the design for broadband improvement is studied at the aids of SSHI (synchronized switch harvesting on inductor) techniques.

9057-49a

Novel model for arbitrary shape bistable piezoelectric-composite plates for vibration-based energy harvesting

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This paper reports a study of improved vibration energy harvesting enabled by considering novel geometries for bistable piezoelectric-composite harvesters. For efficient broadband harvesting it is necessary to tune the operating frequencies, typically achieved through geometry and mass variation, and to introduce nonlinearities, often achieved using magnets. A solution which allows design for both aspects through geometric variables only is to exploit bistability in asymmetric composite laminates. Bistable composites offer large displacements due to a snap-through mechanism between two cylindrical configurations. This property makes them suitable for piezoelectric energy harvesting by repeatedly straining a surface-bonded piezoelectric Macro Fibre Composite. To date, studies have been restricted to rectangular plates. The use of arbitrary planforms significantly widens the design space in search of a design to maximise power output and minimise required base excitation. In this paper we present a novel model to determine the static configurations for arbitrary shapes through discretisation of the planform by a grid of square elements. The static shapes are mapped to a dynamics model to characterise the energy harvesting potential subject to base excitation. Results are presented for analytical modelling and experimental studies for a wide range of planforms to form a comprehensive investigation of the reduction in required excitation, and the large power outputs achievable for broadband operation.

9057-50a

Dielectric loss against piezoelectric power generation

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Dielectric loss is one of the important parasitic features of piezoelectric materials; nevertheless, its role in practical piezoelectric energy harvesting (PEH) systems has not been thoroughly studied in previous literature. Based on the integrated equivalent impedance network model, this paper investigates the susceptibility of harvested power in PEH systems under different dielectric loss conditions. It shows that, dielectric loss always counteracts piezoelectric power generation in PEH systems by causing charge leakage across piezoelectric capacitance. In particular, taking corresponding ideal lossless cases as reference, the relative counteractive effect might be aggravated under either of the five conditions: larger dielectric loss tangent, lower vibration frequency, further away from resonance, weaker system coupling, and larger electrically induced damping. These new understandings are valuable for the study of PEH systems, because they not only help explain the role of dielectric loss in piezoelectric power generation, but also add insights for material, excitation, structure, and circuit considerations towards holistic evaluation and design scheme for practical PEH systems.

9057-51b

Folding patterns and shape optimization using SMA-based self-folding laminates

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Origami engineering, which is the practice of creating useful three-dimensional structures through folding and fold-like operations applied to initially two-dimensional entities, has the potential to impact several areas of manufacturing and design. In some circumstances, however, it may be impractical to exert external manipulations to generate the desired folds (e.g., as in remote applications such as space systems). In such circumstances, self-folding capabilities are necessary. In this paper, a self-folding composite laminate that consists of two outer layers of thermally actuated shape memory alloy (SMA) wire meshes separated by an inner insulating layer is considered. The self-folding laminate is studied using an analysis framework consisting of a finite element solver invoking a coded implementation of a custom SMA constitutive model. The self-folding laminate is utilized to create periodic folding patterns such as the Miura-Ori. In addition, optimization methods are utilized to determine the applied temperature field that would allow the self-folding laminate to morph into desired goal shapes and to meet desired structural characteristics. The results show that the self-folding laminate has attractive characteristics as a future reconfigurable material system which is able to configure into desired shapes and meet certain structural needs without application of external forces.

9057-52b

Low-cost flexible Cu-based shape memory alloys

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Despite their lower cost metal inputs as compared to Nitinol, Cu-based shape memory alloys (SMAs) are not widely used in practical applications due to their brittleness in polycrystalline form. We fabricate Cu-based SMA wires and process them to form a bamboo-type grain structure, i.e., where the wire diameter is completely spanned by individual grains. The wires have diameters ranging from ~500 down to ~20 microns and are free of triple junctions. Our thermomechanical tests show that this structure avoids premature fracture and plastic yielding, which leads to large superelastic strain recoveries of up to 8%, excellent shape memory properties and long fatigue life. The manufacturing method we use is cheap and readily scalable, which makes these Cu-based wires promising candidates for mass-market applications of SMAs, such as in actuation and vibration control.

9057-53b

Smart hybrid rotary damper

Chuang-Sheng Walter Yang, Georgia Institute of Technology (United States)

This paper develops a smart hybrid rotary damper using a re-centering smart shape memory alloy (SMA) material as well as conventional energy-dissipating metallic plates that are easy to be replaced. The ends of the SMA and steel plates are inserted in the hinge. When the damper rotates, all the plates bend, providing energy dissipating and re-centering characteristics. Such smart hybrid rotary dampers can be installed in structures to mitigate structural responses and to re-center automatically. The damaged energy-dissipating plates can be easily replaced promptly after an external excitation, reducing repair time and costs. An ABAQUS model of a smart hybrid rotary was established and calibrated to reproduce the realistic behavior measured from a full-scale experimental test. Furthermore, the seismic performance of a 3-story moment resisting model building with smart hybrid rotary dampers designed for downtown Los Angeles was also evaluated in the OpenSEES structural analysis software. Such a smart moment resisting frame exhibits perfect residual roof displacement, 0.006”, extremely smaller than 18.04” for the conventional moment resisting frame subjected to a 2500 year return period ground motion for the downtown LA area (an amplified factor of 1.15 on Kobe earthquake). The smart hybrid rotary dampers are also applied into an eccentric braced steel frame, which combines a moment frame system and a bracing system. The results illustrate that adding smart hybrid rotaries in this braced system not only completely restores the building after an external excitation, but also significantly reduces peak interstory drifts.

9057-54b

Joining shape memory alloys to bismaleimide-based polymer matrix composites: an interfacial study

Hieu Truong, Ozden Ochoa, Dimitris C. Lagoudas, Texas A&M Univ. (United States)

Hybrid composite laminates have found applications in many different fields such as aerospace structures and microelectronics. Made of different constituents – metal and polymer matrix composites, the bonding and delamination at the interfacial regions in these laminates

remain as the most critical concerns. In this study, Nitinol (NiTi) strips are joined to plain weave T300/Matrimid 5292 composite (PMC) and the NiTi-PMC interface in the resulting hybrid laminates is investigated. Herein, surface treatments on Nitinol include etching, sand-blasting and sol-gel methods. Matrimid 5292 is used as adhesive to bond NiTi to PMC. The whole assembly is appropriately clamped and co-cured in a hot-press, following the same curing cycle used to make the laminates. Differential scanning calorimetry (DSC) is performed on the PMC before and after joining process to study the effect of multiple curing cycles on the thermal and mechanical behaviours of PMC. Besides imaging techniques such as optical microscopy and scanning electron microscopy, nanoindentation and energy-dispersive X-ray spectroscopy (EDS) are carried out to obtain the local mechanical properties and elemental composition at the SMA-PMC interface. In-situ DIC and four-point bending tests of the fabricated NiTi-PMC bimaterial beams are carried out at room temperature. Results from bending tests and DIC analyses are compared with analytical solutions and finite element models. It is suggested that sol-gel treated interface yields the best performance compared to interface treated with other methods, and can reached as high as 82% values obtained from FE models with perfect bonding assumption. Current efforts are expanding to incorporate piezoelectric sensor arrays to the NiTi-PMC interface and investigating mechanics of the NiTi-PMC beams with and without sensors as well as sensor arrays' functionalities during thermal or mechanical loading of beams.

9057-56a

Active healing of delaminated composite structure using piezoelectric actuator

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Recently, light weight structure becomes an object of attention because increase of energy efficiency becomes the most important global hot issue. Then, composite structures, which have inherent high strength and stiffness to weight ratio, are in the limelight for light weight structures. However, complex failure modes of composite structure are still remains unsolved problem and become main obstacle of wide application of composite structures. Delamination is one of frequent damage phenomenon of laminated composite structure. Delamination can cause reduction of structural stiffness and decrement of natural frequencies. This might induce increase of structural vibration and resonant phenomenon of operating structures. Then, delamination should be detected and complemented. In this work, active control scheme and piezoelectric actuators are used to reduce the delamination effect of damaged composite structure. At first, finite element model for delaminated composite structure is constructed based on improved layerwise theory and then state space control model is established. After design and implementation of active controller, dynamic characteristics and structural performances of damaged composite structure are investigated and effectiveness of active healing is evaluated.

9057-57a

Design of acoustic lenses by means of granular chains

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In the last decade, there has been an increasing attention on the use of highly- and weakly- nonlinear solitary waves in engineering and physics. These waves can form and travel in nonlinear systems such as one-dimensional chains of particles. When compared to linear elastic waves, solitary waves are much slower and possess the unique characteristics of exhibiting constant spatial wavelength, compact-supportedness, and amplitude-dependent speed. One interesting engineering application of solitary waves is the fabrication of acoustic lenses, which are employed in a variety of fields ranging from biomedical imaging and surgery to defense systems and damage detection in materials.

In this paper we propose the design of acoustic lenses composed by one-dimensional chains of spherical particles arranged to form a line or a circle array. We show, by means of numerical simulations and an experimental validation, that both the line and circle arrays allow the focusing of waves transmitted into a solid or liquid (the host media) and the generation of compact sound bullets of large amplitude. The advantages and limitations of these nonlinear lenses to attain accurate high-energy acoustic pulses with high signal-to-noise ratio are discussed.

9057-58a

Implementation of modified positive velocity feedback controller for active vibration control in smart structures

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This paper introduces the Modified Positive Velocity Feedback (MPVF) controller as an alternative to the conventional Positive Position Feedback (PPF), with the goal of suppressing both displacement and velocity of resonant vibrations in smart structures. The MPVF controller uses two parallel feedback compensators working on the fundamental modes of the structure. The vibration velocity that is measured by a sensor or state estimator is fed back to the controller as the input. To control n-modes, n sets of parallel compensators are required. MPVF controller gain selection in multimode cases highly affects the control results. This problem is resolved using the Linear Quadratic Regulator (LQR) and the M-norm optimization method, which are selected to form the desired performance of the MPVF controller. First, the controller is simulated for the two optimization approaches, then experimental investigation of the vibration suppression is performed. The LQR-optimized MPVF provides a better suppression in terms of vibration displacement. The M-norm-optimized MPVF controller focuses on modes with higher magnitudes of velocity, it provides a higher level of vibration velocity suppression than LQR-optimized method. Vibration velocity attenuation is important in preventing fatigue failures due to the fact that velocity can be directly related to stress.

9057-59a

Design of acoustic waveguides using multiresolution topology optimization

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In this work the Multiresolution Topology Optimization (MTOP) scheme is investigated to obtain high resolution designs of phononic (elastic) materials, focusing primarily on acoustic waveguides. As the name suggests, the purpose of an acoustic waveguide is to facilitate the propagation of elastic waves through a given design domain in a desired fashion. MTOP allows obtaining high resolution designs with relatively low computational cost, by using three distinct discretization levels for the topology optimization procedure. The main idea is to employ a coarser discretization for finite elements and finer discretization for both density elements and design variables. Numerical examples illustrate that the resolution of the design can be significantly improved without refining the finite element mesh. The first example presented in this work is the simplest case where one might be interested in maximizing the energy reaching certain parts of the domain. The second and more interesting example is the creation of different propagation patterns for different frequencies, thus creating smart filters or band-gap devices (as opposed to simple filters/band-gap devices, which simply block wave propagation for a few certain prescribed frequencies). The results demonstrate the power and potential of our computational framework to design sophisticated acoustic wave devices.

9057-60a

Implementation of a modal disturbance estimator for vibration suppression

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Fiber Bragg Gratings (FBG) sensors have a great potential in active vibration control of smart structures thanks to their small transversal size and the possibility to make an array of many sensors. They can be embedded in carbon fiber structures and their effect is nearly negligible.

This paper presents a control strategy for the suppression of vibration due to unknown disturbance forces in large, nonlinear flexible structures. The control action proposed, based on the modal approach, consists of two contributions. The first is the well-known Independent Modal-Space Control, which increases system damping and improves its behavior close to the resonance frequencies. The second is a disturbance estimator, which calculates the modal components of the external forces acting on the system and compensates for them using actuator forces. The system modal coordinates, required by both logics, are estimated through a modal state observer.

The work shows how the use of FBG sensors allows improving the performance of the control to suppress vibration. The advantage mainly consists on the opportunity to have a large number of measurements regarding the state of deformation of the whole structure.

The proposed control logic is tested on a carbon fiber smart structure composed of a thin cantilever beam with 14 longitudinal FBG sensors and 3 piezoelectric actuators (PZT).

9057-118a

Design considerations for small-scale wind energy harvesters driven by broadband vortex-induced vibrations

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Presently, there is great interest in exploring alternative energy sources, such as wind power, within the scientific community. While many studies focus on large-scale energy production, there exist a variety of applications in the small-scale realm as well. At these small scales where boundary layer effects are appreciable, wind interaction with structures can be exploited using piezoelectric materials to harvest usable electrical energy. This paper presents and discusses a study on energy extraction utilizing vortex-induced vibrations induced by the unsteady shedding of the boundary layer flow over a bluff body. The model under consideration consists of a piezoelectric cantilever attached to the trailing edge of a miniature rigid bluff body on the order of tens of millimeters in diameter. Under these conditions, the beam is subjected to transverse vibrations due to periodic pressure fluctuations associated with shedding vortices around the bluff body. This model is specifically designed for laminar Reynolds Number flows where the periodicity of vortex shedding approaches the natural frequency of the beam. Near this natural frequency, the phenomenon of lock-in occurs where the vortex shedding frequency remains 'locked-in' over a range of Reynolds Numbers. Vibration amplitudes of the beam reach a maximum under this condition, thus maximizing power output of the system. Parameters of particular interest in this study include bluff body geometry, beam length, beam natural frequency, and Reynolds Number. Special consideration is given to the effect of the bluff body shape on vortex shedding behavior. The influence of these parameters are studied utilizing COMSOL Multiphysics laminar, fluid-structure interaction simulations in an effort to compare results such as lock-in bandwidth, average power generation, and the time required for a fully-developed flow, in order to create design guidelines for an energy harvester based on expected flow conditions.

9057-61b

Broadband sound attenuation on a periodic array of rectangular profile holes in plate

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The transmission of acoustic waves through a periodic array of sub-wavelength slits or holes have been studied in several recent works in relation with physical phenomena such as resonant (extraordinary) transmission, broadband sound shielding or acoustic induced transparency. In this work, we present for the first time the study of analogous phenomena for Lamb waves propagating in a thin plate. The resonances and anti-resonances on series of parallel rows, of periodically arranged rectangular slits separated by holes, are investigated as a function of the geometrical parameters of the slits, especially in the sub wavelength regime. With only one row of slits, the features in the transmission coefficient are explained in terms of the coupling of the incident waves with the Fabry-Perot oscillations inside the slits and with the localized modes at the boundaries between the slits and homogeneous plate. We discuss the dependence of selective and zero of transmission frequencies, in particular Fano resonances resulting from the proximity of a resonance with a zero of transmission. When a second row of slits is added, the choice of the distance between both rows allows for the realization of a broadband attenuation in the transmission up to 99%. With additional rows of slits we find the properties of a phononic crystal constituted by a periodic array of holes in a plate. These investigations should have implications for sound isolation, imaging and sensing applications.

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9057-62b

Semi-active vibration control of a flexible space structure using MFC actuators

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With the rapid development of aerospace industry, the antenna structures evolve in the direction of larger size, lower stiffness and higher flexibility, which leads to very low fundamental vibration frequency and damping factor, so that their vibration excited by attitude control and other disturbances takes very long time to decay. Therefore, vibration reduction is a critical issue related to maneuvering of flexible antenna structure and improvement of positioning precision.

In this paper, a study on vibration control of a flexible space structure is presented. A simplified mechanical model of a flexible satellite with two symmetrical antennas is considered. The main body of satellite is supposed to be fixed and the antenna is modeled as a lumped mass at the free end of the elastic arm. MFC (Macro Fiber Composite) piezoelectric actuators are bonded on the surface of the elastic arm and semi-active method called synchronized switching damping (SSD) approach is used to control the MFC actuators. First the dynamic characteristics of the simplified system are analyzed using FEM method and a space state model is derived from the numerical results. Second, a switch circuit is designed and constructed. The semi-active control algorithm is implemented on a dSPACE system. An experimental system consisting of the simplified satellite model and the semi-active control system was constructed. The experimental results indicate that the control system is effective in suppressing the vibration of the antenna.

9057-63b

A study on vibration control method of building structure using macro-fiber composite

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Recently, sheeted or fibrous piezoelectric devices have been actively developed as actuators or sensors. These light and flexible devices are expected to create many possibilities for innovations of method for vibration control of structures.

In this paper, we discuss on a new active control method of vertical and horizontal micro-vibration of an architectural frame structure using Macro-Fiber Composite (MFC). MFC is sheeted piezoelectric devices constructed with fibrous piezoseramics and it has capability to produce relatively higher forces than other sheeted piezoelectric devices.

We propose that MFCs are arranged at the lower flange of the both ends of the beam as actuators. By the expansion and contraction movements of MFC actuators, bending moments act at the both ends of the beam. Synchronized movements of MFC actuators act as control force for vertical vibration of beam or slab. Opposite phase movements act as control force for horizontal vibration of frame structure. Other MFC as a sensor is arranged at an arbitrary position of the lower flange surface.

Principle experiment of?vertical and horizontal vibration control on about 1/3 scaled frame model is conducted, and the result show the control method is effective to reduce the resonantly generated vibration. Vertical vibration control test on a real architectural structure is also conducted. MFCs are arranged at the ends of two beams spanning girders. As the result, vertical floor vibration of 0.04 m/s2 at 8.5 Hz at the center of the grid was reduced to 0.01 m/s2 or about -12 dB.

9057-64b

Optimal synthesis of passive adaptive structural networks for damping and stiffness improvement

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The increasing interest in the development of systems with excellent vibration control and shock mitigation has fostered the novel design approaches which provide easily scalable systems with passive adaptive performance across the different fields of engineering. In this paper we present a novel modular design concept to synthesize passive adaptive structures upon a varied loading condition. This concept assumes the existence of a set of linear and nonlinear structural elements that can be selected and interconnected depending on the scale and performance requested to the final structural assembly. To realize this concept we developed a structural assembly design tool integrated with the genetic algorithm for the synthesis of the optimal structural assembly. The design optimization problems with single- and multi-objective functions are formulated considering the prescribed design requirement on stiffness and damping performance. This tool optimally synthesizes the structural network by assembling the available constitutive elements in the set and successfully obtains passive adaptive assembly upon a varied loading condition in terms of vibration amplitude and frequency.

9057-65b

An optimal approach in negative derivative feedback control gain synthesis

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Vibration control logics based on the modal approach allow to increase damping on a certain number of modes. The main limit associated with these strategies is represented by spillover. This phenomenon occurs when non modeled modes alter state reconstruction (observation spillover) or when they are excited by control forces (control spillover). These effects can worsen the control performance or even lead to instability. In order to reduce this problem, different strategies has been proposed. In this paper the “resonant controls” framework is analyzed. All these solutions are characterized by a control force opposite in phase with respect to the modal velocity in a restricted range of frequencies. Among these logics, Negative Derivative Feedback (NDF) has shown to be particularly robust against spillover: modal velocity is fed back through a second order band-pass filter so that undesired effects on other modes can be limited both at lower and higher frequencies with respect to the controlled mode resonance. NDF dynamics can be described by a second order differential equation whose coefficients affect the resulting performance in terms of damping of the mechanical system and robustness to spillover. In particular a design strategy is proposed based on an optimal approach. The mechanical system and control dynamics equations have been rearranged in order to obtain an output feedback control problem. A control design optimal approach is adopted. The methodology has been developed in case of one and multi-degrees of freedom systems and tested on cantilever beam finite element model.

9057-66b

Seismic responses of asymmetric reinforce concrete framed structures equipped with viscous wall dampers

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Recently many types of lateral resistance systems and earthquake energy dissipation device for structures subjected to ground motion have been studied. However, viscous dampers are more popular and widely used among of other structural control systems. Especially viscous wall damper is more considered to use in steel frames due of its high performance, ease to install and low cost. Although there is no enough investigation on implementing viscous wall damper in asymmetric buildings and reinforced concrete structures.

So, this paper is focused on investigation seismic responses of asymmetric reinforce concrete (RC) frame structures equipped with viscous wall dampers. For this purpose three story RC building is considered and three dimensions finite element model of RC structure consist of beam and column elements is developed and effect of viscous wall damper is applied to the structures. So, time history analysis of model is carried out and effect of implementing viscous wall damper in response of RC structure subjected to earthquake excitation is evaluated. Also an attempt has been made to study effect of viscous wall damper location in structure plan in seismic response of irregular frame building.

The result of analysis is investigated in terms of story displacements and structural member forces and proved that viscous wall damper effectively decreased seismic response of structure. Also, investigation on location of wall damper device reveals that implementing dampers in outer frames of structure effectively increased damper performance on dissipating of earthquake energy.

9057-67a

Nonlinear modeling, strength-based design, and testing of flexible piezoelectric energy harvesters under large dynamic loads for rotorcraft applications

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There has been growing interest in enabling wireless health and usage monitoring for rotorcraft applications, such as helicopter rotor systems. Large dynamic loads and acceleration fluctuations available in these environments make the implementation of vibration-based piezoelectric energy harvesters a very promising choice. However, such extreme loads transmitted to the harvester can also be detrimental to piezoelectric laminates and overall system reliability. Particularly flexible resonant cantilever configurations tuned to match the dominant excitation frequency can be subject to very large deformations and failure of brittle piezoelectric laminates due to excessive bending stresses at the root of the harvester. Design of resonant piezoelectric energy harvesters for use in these environments require nonlinear electroelastic dynamic modeling and strength-based analysis to maximize the power output while ensuring that the harvester is still functional. This paper presents a mathematical framework to design and analyze the dynamics of nonlinear flexible piezoelectric energy harvesters under large base acceleration levels. Specifically a strength-based limit is imposed to design the piezoelectric energy harvester with a proof mass while accounting for material, geometric, and dissipative nonlinearities. Experiments are conducted at different excitation levels for validation of the nonlinear design approach proposed in this work.

9057-68a

Electret properties of PVDF film material: flexible and lightweight energy harvesting device

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An electrostatic energy harvesting device is presented that is not build with MEMS technology, but like a film capacitor.

Initially, the setup was intended for the use of the piezoelectric effect of PVDF films. Two layers of PVDF film and two Aluminum foils are stacked alternating and rolled on a winding mandrel. Afterwards the rolled laminate is flattened.

By using separated Aluminum foils, PVDF showed its electret properties. The distance between PVDF film and Aluminum foil can be changed by compressive forces if the device is just loosely wound. The change of the distance in addition to the polarized PVDF film acts like an electrostatic generator. A comparison of metallized PVDF film devices with not metallized PVDF film devices showed the big influence of the electret effect. Metallized film devices have significantly lower electrical output energy.

The biggest challenge in the design of the device is to ensure a controllable change of distance between PVDF film and Aluminum foil if the device is stressed mechanically. One possibility is the change of parameters of the winding process to generate certain pretensions of the films. The disadvantage of this method is that it is very difficult to produce devices with constant properties.

One potential solution for this problem is to fold the device in a special way. The advantage of the fold is that the distance of the electrodes changes in a more controlled and uniform way, if it is pushed and pulled. The solution is implemented practically right now and examined for its suitability.

9057-69a

Performance enhancement of piezoelectric energy harvesting system using corrugated cantilever beam

Jeongsu Park, Hyung-Jo Jung, SeungSeop Jin, In-ho Kim, KAIST (Korea, Republic of)

In this paper, a piezoelectric energy harvesting device consisting of a proof mass and a corrugated cantilever beam is proposed in order to enhance its performance (i.e., an increase in output voltage as well as a reduction in resonant frequency). The sinusoidal or trapezoidal shape of the cantilever beam is able to make the bonding area of piezoelectric material (e.g., polyvinylidene fluoride (PVDF) film) much larger, resulting in high output voltage. Moreover, the natural frequency of the device can be significantly decreased due to low flexibility of the beam member. This may be good for civil engineering applications because most civil structures such as bridges and buildings have low natural frequencies. In order to examine the geometrical characteristics of the proposed device, analytical development and numerical simulation are carried out. Besides, shaking table tests are also conducted with a prototype of the device. It is demonstrated from numerical and experimental studies that the proposed energy harvester can shift down its resonant frequency considerably and generate much higher output power than the conventional one having a flat (or straight) cantilever beam.

9057-70b

Improved negative capacitance shunt damping with the use of acoustic black holes

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Negative capacitance shunt damping is an effective broadband method for attenuating flexural vibration. However, proper selection of the location of the piezoelectric patches on a structure to maximize reduction has been an ongoing question in the field. Acoustic black holes are a recently developed concept to reduce vibrations on thin vibrating structures. By engineering the geometric or material properties of these thin structures, it is possible to minimize the reflected wave by gradually reducing the wave speed. However, the flexural wave speed cannot be reduced to zero on a realized structure. Therefore, when acoustic black holes are implemented, some of the incident wave energy is reflected because the wave speed must be truncated. Similarly due to the reduction in wave speed, the transverse velocity significantly increases within the acoustic black hole. It is therefore possible to add piezoelectric transducers to acoustic black hole regions on a structure to utilize negative capacitance shunt damping to address both of these issues. Consequently, the transducers are placed in the locations where the greatest control can be made and the reflected waves can be attenuated. The combination of negative capacitance shunt damping with acoustic black holes shows increased suppression of vibration over shunt damping alone.

9057-71b

Optimal placement of piezoelectric actuators on plate structures for active vibration control using genetic algorithm

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The present work considers the optimal placement of piezoelectric actuators on a thin plate using integer coded genetic algorithm. The fitness function reflects on the controllability index which is the singular value of a control matrix. The index measures the input energy required to achieve the desired structural control using piezoelectric actuators. The controllability index is dependent on the size and position of the piezoelectric patches and minimum control effort is achieved by maximizing the index and hence optimal placements of the piezoelectric actuator can be obtained. The problem has been formulated using the finite element method (FEM) using eight collocated piezoelectric sensors and actuators on a square cantilever and simply supported plate. The

contribution of the piezoelectric sensor and actuator layers on the mass and stiffness of the plate has also been considered while modeling the entire structure in a state space form. Classical control strategy like direct proportional feedback and the LQR (Linear Quadratic Regulator) optimal control scheme have been applied to study the control effectiveness. It is observed that the frequency responses of cantilever & simply supported square plate hold good in agreement with the experimental results. Numerical simulations revealed that optimal locations obtained by integer coded GA based on controllability index with LQR controller offers effective control with lower peaks voltages as compared non-optimal locations.

9057-72b

Application of viscous damper devices in light rail transit station

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Nowadays light rail transit (LRT) system is more desired to use due to improvement of travel option, sustainability and facilitating swift mobility in urban area. Hence, structural stability and safety of these public transportation against the seismic occurrences is indispensable.

In the present paper, the LRT station located in Malaysia is considered and seismic response of train station with supplementary viscous damper devices is evaluated. So, LRT station is modeled using finite element method via beams, columns, space frame (curved trussed arched frame as roof) and viscous dampers. In order to evaluate damper effect on structural seismic response, two model of structure with and without damper device are considered and time history analysis of LRT station subjected to Elcentro earthquake excitation (US, 1940) was performed.

The seismic response assessment reported in terms of structural displacements as well as base shear. The result indicated that implementing of viscous dampers have a significant decrease in response of structure during earthquake excitation. The time history displacement of joints at the top of the tubular roof for structure model with and without damper device and indicated about 40% displacement reduction in model equipped with dampers. Furthermore, two joints at the tip of the RC column/piers illustrated an approximate 90% displacement reduction. The comparison in terms of base shear at both models (without damper and with damper) indicates an approximate of 60% base shear reduction. The efficiency of implementing damper device in seismic response of structure has been visibly demonstrated by the analysis result.

9057-73a

Nonlinear forced response of piezoelectric microcantilevers with application to tapping mode atomic force microscopy

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Atomic Force Microscopy (AFM) uses a scanning process performed by a microcantilever beam to create a three dimensional image of a nano-scale physical surface. AFM includes a microcantilever probe with a tip at the end that is controlled in order to keep the force between the tip and the surface constant by changing the distance of the microcantilever from the surface. Some microcantilevers have a layer of piezoelectric material on one side of the microcantilever for actuation purpose. An accurate understanding of the microcantilever motion and tip-sample force is needed to generate accurate imaging. In this paper, the equations of motion for a piezoelectric microcantilever are derived for a nonlinear contact force. The analytical expressions for natural frequencies and mode shapes are obtained. Then, the method of multiple scales is used to analyze the analytical frequency response of the piezoelectric probe. The effects of nonlinear excitation force on the microcantilever beam's frequency and amplitude have been analytically studied. The results show a frequency shift in the response resulting from the force nonlinearities. This frequency shift during contact mode is an important consideration in the modeling of AFM mechanics for generation of more accurate imaging.

9057-74a

Chemical wet etching of PZT (lead-zirconate-titanate)

Marc C. Wurz, Sebastian Bengsch, Lutz Rissing, Leibniz Univ. Hannover (Germany)

Piezo-electric materials are often mentioned in relation with the term of "Energy Harvesting". These Materials are producing an electric surface charge when a compression load or a tensile load is applied. This attribute of piezo-electric materials is promising regarding "Energy Harvesting". At this point, micro technology could play the key role. The development of energy autonomous systems seems to be a goal which will be very important in future, to reduce the demand of resources and the environmental impact. Concerning these points the thought about optimizing the already existing system ideas is arising. The project deals with the idea of structuring PZT bulk materials to produce higher efficient piezo-electric harvesting systems to minimize the gap to an autonomous sensor system. Therefore the chemical wet etching process of PZT materials appears to be promising. Investigations on the behavior of PZT materials are a main part of this project. As well as the ability of structuring PZT with different types of masks and acid solutions. The results of the project are promising a future of the wet chemical processing of PZT materials to structure different shapes as a basic process to fabricate PZT elements for Energy Harvesting Systems.

9057-75a

Theory of suspended carbon nanotube thinfilm as a thermal-acoustic source

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Most of the traditional sound transducers with a peak performance at the mechanical resonant frequency nowadays are narrow-banded. The thermal-acoustic sound transducer generated by a heated suspended carbon nanotube- (CNT) thinfilm, as shown in this paper, is wide-banded with no resonance for a wide range of frequencies. The thermal acoustic mechanism principle is different from the traditional approach which is based on mechanical vibration. In this paper, accurate analytical solution for thermal-acoustic radiation from a suspended CNT thinfilm is obtained for near- and far-fields by constructing a coupled thermal-mechanical CNT model and solving for the thermally induced acoustic response. Using appropriate simplifications, a brief and concise solution is obtained within a certain frequency range. By comparing the analytical prediction with experiment result, it is concluded that the approximate analytical solution is sufficiently accurate. From the analytical solution, the heat capacity per unit area significantly influences the acoustic pressure. A CNT-thinfilm with a smaller heat capacity per unit area improves acoustic pressure. In addition, it is found that acoustic wave at a higher frequency remains as a plane wave for a longer distance and it maintains a wideband constant (flat) amplitude-frequency response in a near-field.

9057-76a

A novel interdigitated, inductively tuned, metal contact capacitive shunt RF-MEMS switch for X and K band applications

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RF MEMS capacitive shunt switches bandwidth is limited by its isolation characteristics. In multi-band systems number of switches required thus will increase as the band changes. This will consume a lot of chip area and can be minimized by multi-band tunable switches. A number of structures have been reported in the literature for the switches which have high isolation but can't be tuned for different bands. In another approach combination of switches like series and shunt are used but requires large area and thus suitable for future compact systems. This paper presents a new type of switch for the above cited purpose. In the proposed design, interdigitation of signal lines with actuation electrodes is used to make a compact device. A central bridge anchored in between ground planes and attached to two cantilevers on either side has been used to implement the switch structure. This novel structure is used to inductively tune the isolation peaks in X and K bands which is not possible with conventional approach. Switch shows an insertion loss of – 0.01 dB to –0.19 dB from 1GHz to 25 GHz when the beams are in up-position. Isolation of -34.89, -34.68, and -39.98 dB has been observed at 10 GHz, 11 GHz and 21 GHz when central beam is electro-statically actuated with either left, right or both cantilevers in the down state respectively. Central beam shows a pull-in voltage of 12.25 V and switching time of 34.40 µs whereas left and right cantilevers have 7.5V and 57 µs.

9057-77b

Micro-fiber composites performance under thermal cycling for SHM applications

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This work focuses on investigating the effects of thermal cycles in the damage detection performance of Micro-Fiber Composites (MFC). A host structure with an MFC bonded to its surface is submitted to a 90 min temperature cycle that varies from -15ºC to 80º C. After each cycle the electrical impedance of the test sample is measure with and without the presence of a representative damage (an added mass). The results indicate that the thermal cycling affects the smart device by changing its impedance profile, a phenomenon that should be taken into account damage detection algorithms.

9057-78b

A Structure Damage Detection Method Based on Wavelet Analysis and Type-2 Fuzzy Logic System

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In this paper, a structure damage-locating method based on a combination of wavelet analysis and a type-2 fuzzy logic system (T-2FLS) is proposed. Firstly, the structure is divided into elements and excited to be vibrated. An adaptive sampling solution is proposed to establish average quantity signal of wavelet transform coefficient (AQWTC) of vibration signal with a used-scale-sheet. The T-2FLS is then used to identify the structure at its undamaged time via AQWTC signal. At checked time, calculating AQWTC at each element is realized to estimate the corresponding difference of AQWTC between two cases: undamaged status and the status at the checked time. Strange features appeared in this compared signal directly represents the beam-damage signs. The effectiveness of the proposed method is demonstrated by experiment on two different data sources; one is from dynamic response of models built by ANSYS and the other is measured data sets from dynamic behavior of real structures.

9057-79b

Haptics using a smart material for eyes free interaction in personal devices

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In this paper we present a prototype using a dry ionic polymer metal composite (IPMC) in interactive personal devices such as bracelet, necklace, pocket key chain or mobile devices for haptic interaction when audio or visual feedback is not possible or practical. This prototype interface is an electro-mechanical system that realizes a shape changing haptic display for information communication. A dry IPMC will change its dimensions due to the electrostatic effect when an electrical potential is provided to them. The IPMC can operate at a lower voltage (1-3V) which is compatible with requirements for personal electrical devices or mobile devices. The prototype consists of the addressable arrays of the IPMCs with different dimensions which are deformable to different shapes with proper handling or customization. 3D printing technology will be used to form supporting parts. Microcontrollers (about 3cm square) from DigiKey will be imbedded into this personal device. An Android based mobile APP will be developed to talk with microcontrollers to control IPMCs. When personal devices receive information signals, the original shape of the prototype will change to another shape related to the specific sender or types of information sources. This interactive prototype can simultaneously realize multiple methods for conveying haptic information such as dimension, force, and texture due to the flexible array design. We conduct several studies of user experience to explore how users' respond to shape change information.

9057-80b

All-printed smart structures: a viable option?

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The last two decades have seen evolution of smart materials and structures technologies from theoretical concepts to physical realization in many engineering fields. These include smart sensors and actuators, active damping and vibration control, biomimetics, and structural health monitoring. Recently, additive manufacturing technologies such as 3D printing and printed electronics have received attention as methods to produce 3D objects or electronic components for prototyping or distributed manufacturing purposes. In this paper, the viability of manufacturing all-printed smart structures, with embedded sensors and actuators, will be investigated. To this end, the current 3D printing and printed electronics technologies will be reviewed first. Then, the plausibility of combining these two different additive manufacturing technologies to create all-printed smart structured will be discussed. Potential applications for this type of all-printed smart structures include most of the traditional smart structures where sensors and actuators are embedded or bonded to the structures to measure structural response and cause desired static and dynamic changes in the structure.

9057-81a

Modeling and design of Galfenol unimorph energy harvester

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Magnetostrictive iron-gallium alloys, known as Galfenol, are a recent class of smart material that can potentially be implemented in energy harvesting applications. Galfenol-based energy harvesters have been designed and tested in previous research. Berbyuk presented a harvester where the vibration was applied along the axial direction. Ueno et al. designed a harvester using a pair of Galfenol beams. Unimorph beams with the active material bonded to a passive substrate have also been considered. Yoo et al. presented a Galfenol unimorph harvester and analyzed its response over a large temperature range. All the harvesters above can only absorb energy from a narrow frequency range, thus techniques for improving the effective bandwidth should be implemented.

Models for Galfenol-based energy harvesters have been developed. Yoo et al. proposed a 1D spring-mass-damper model and an optimal Galfenol unimorph harvester has been designed based on this model, but the model significantly over predicts the output voltage. Rezaeealam et al. set up a 3D anhysteretic FEA model in COMSOL Multiphysics, but this model is quasi-static.

To overcome the limitations of previous unimorph harvester models, a fully 3D hysteretic energy averaged Galfenol model is proposed and implemented in COMSOL Multiphysics. Based on this model, this study first designs geometry parameters including thickness ratio and tip mass according to the natural frequency requirement imposed by the application. Second, the strength and position of the magnets are selected to guarantee the unimorph beam exhibits chaotic response over the desired frequency range. Finally, experiments are conducted to validate the simulation results.

9057-82a

Tapered piezoelectric devices for vibration energy harvesting

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The effect of tapering cantilevered piezoelectric devices has been reported in literature by researchers for enhancement of transversal strain through the length of the beam. However, simply tapering a beam while maintaining the length effectively doubles the devices resonance frequency, which diminishes the effect of enhanced strain; but it nevertheless enhances the loading capacity of the structure. In this study, singular tapered geometries while maintaining the beam's mass and resonance frequency of a piezoelectric device compared to a rectangular counterpart are first explored, showing improved power generation characteristics. Further, the goal of this study is to extend this concept for novel shaped devices, which includes a triangular device that is clamped in the center, and loaded on three sides. Similarly, a hexahedral (star) shaped device that is clamped in the center with five extending triangles is presented. Such clamping configurations increase the opportunities for loading these structures with equally distributed loading, or uneven loading for passive tuning of piezoelectric energy harvesters. Another concept that is explored is of finned/gilled triangular structures for further increasing the number of fundamental frequency modes within the structure. The effect of number of fins is explored. These structures have been evaluated for piezoelectric power generation.

9057-83a

Low-frequency acoustic energy harvesting

Bin Li, Jeong Ho You, Southern Methodist Univ. (United States)

As a green, prevalent and sustainable energy, acoustic energy is abundant in our life and currently wasted. In this study, a novel and practical acoustic energy harvesting mechanism to harvest travelling sound at low audible frequency (~200 Hz) is introduced and studied both experimentally and numerically. The harvester contains a quarter-wavelength straight tube resonator with multiple piezoelectric cantilever oscillators placed inside the tube. When the tube resonator is excited by an incident sound at its acoustic resonance frequency, the amplified acoustic pressure inside the tube drives the vibration motions of piezoelectric oscillators, resulting in generating electricity. Acoustical resonant behavior inside the resonator with the presence of piezoelectric oscillators is studied by numerically simulation. A large pressure gradient, which is the driving force of vibrating oscillators, is available near the open inlet. Thus it is more deserved to place the oscillators in the first half of the tube rather than in the entire tube. The number of oscillators to maximize the voltage and power is limited due to the interruption of air particle motion by oscillators. The output voltage increases linearly with the incident sound pressure. Additionally, self-powered synchronized switch harvesting on inductor (SSHI) circuit has been introduced in the harvester to convert AC output from the vibrating multiple piezoelectric oscillators to DC, in order to charge terminal electric load such as electrochemical battery.

9057-84a

Concepts in energy harvesting for marine wildlife monitoring

Michael W. Shafer, Northern Arizona Univ. (United States)

There have been a number of new applications for energy harvesting with the ever-decreasing power consumption of microelectronic devices. In this paper we explore a new area of marine animal energy harvesting for use in powering tags known as bio-loggers. These devices record data about the animal or its surroundings, but have always had limited deployment times due to battery depletion. Reduced solar irradiance below the water's surface provides the impetus to explore other energy harvesting concepts beyond solar power for use on marine animals. We review existing technologies in relation to this application. Additionally, we propose a new idea for energy harvesting that uses hydrostatic pressure changes as a source for energy production. The application of these concepts in the arena of bio-logging technology could substantially increase bio-logger deployment lifetimes, allowing for measurements over the course of multiple years.

9057-85b

Vibration control of plates through a periodic array of shunted piezoelectric patches with negative capacitance circuits

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In the last few decades, researchers have given a lot of attention to new engineered materials with the purpose of developing new technologies and devices such as mechanical filters, low frequency sound and vibration isolators, and acoustic waveguides.

For instance, elastic phononic crystals may come to mind. They are materials with elastic or fluid inclusions inside a matrix made of an elastic solid. The anomalous behavior in phononic crystals arises from interference of waves propagating within an inhomogeneous material. The inclusions inside the matrix cause strong modifications of scattering properties. However, the application of phononic crystals is still limited to sonic frequencies.

In fact, band gaps can be generated only when the acoustic wavelength is comparable to the distance between the inclusion.

In order to overcome this limitation, a new class of metamaterial has been proposed: meta composite. This new class of material can modify the dynamics of the underlying structure using a bidimensional array of electromechanical transducers, which are composed by piezo patches connected to a synthetic negative capacitance.

In this work, a finite element-based design methodology is used to predict the reflective and attenuation properties of the the periodic assembly. The predictions are experimentally validated by measuring the out-of-plane displacements and the averaged kinetic energy of the controlled smart plate. The resulting data clearly show how this proposed technique is able to dampen and selectively reflect the incident waves.

9057-86b

Evaluation of magnetostrictive shunt damper performance using Iron (Fe)-Gallium (Ga) alloy

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Iron–gallium alloys (galfenol) are promising transducer materials that combine high magnetostriction, desirable mechanical properties, high permeability, and a wide operational temperature range. In this study, we present results from a proof-of-concept prototype shunt vibration damper. The device consists of a polycrystalline galfenol strip bonded to a brass cantilever beam. Two brass pieces, each containing a permanent magnet, are used to mass load each end of the beam and to provide a magnetic bias field through the galfenol strip. The voltage induced in an induction coil closely wound around the cantilever beam captures the time rate of change of magnetic flux within the galfenol strip as the beam vibrates. The first bending-mode resonant frequency of the device was 68 Hz. To dissipate the electrical voltage from the device, a shunt, or a load, is attached. With careful tuning the shunt can increase the efficiency of the magnetostrictive damper. The ideal levels of resistance and capacitance in the shunt are investigated to maximize the shunt damper performance.

9057-87b

Suppression of mechanical vibrations in a building-like structure using a passive/active autoparametric absorber

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An experimental investigation is carried out on a system consisting of a primary structure coupled with a passive/active autoparametric vibration absorber. The primary structure consists of a building-like mechanical structure, it has three rigid floors connected by flexible columns made from aluminium strips, while the absorber consists of a cantilever beam with a PZT patch actuator actively controlled through an acquisition card. The overall system is modeled using finite element analysis and validated using experimental modal analysis techniques. The whole system, which is a coupled non-linear oscillator, is subjected to sinusoidal excitation obtained from an electromechanical shaker in the neighborhood of internal resonance. The natural frequency of the absorber is tuned to be one-half any of the natural frequencies of the main system. With the addition of a PZT actuator, the autoparametric vibration absorber is made active, thus enabling the possibility to control the effective stiffness associated to the passive absorber and, as a consequence, the implementation of an active vibration control scheme able to preserve, as possible, the autoparametric interaction as well as to compensate varying excitation frequencies. This active vibration absorber employs feedback information from an accelerometer on the primary structure, an accelerometer on the tip beam absorber and a strain gage on the base of the beam, feedforward information from the excitation force and on-line computations from the nonlinear approximate frequency response, parameterized in terms of a proportional gain provided by a voltage input to the PZT actuator, thus providing a mechanism to asymptotically track an optimal, robust and stable attenuation solution on the primary system.

9057-88b

Study on vibration control of reinforced concrete structures based on OpenSees platform

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In recent years, structural control has attracted considerable attention as an advanced hazard mitigation strategy to alleviate wind and seismic response of buildings and bridges. It can effectively increase the safety and performance of a traditional design by redistributing and dissipating the energy of the structure. The current state-of-practice is that Matlab is developed as the most popular software to simulate such structural control problem. This is evident in the different approaches used by researches in analyzing control problem. However, Matlab cannot conveniently build elaborate model for civil structures comparing to finite element software, especially for nonlinear structural model. Due to the severity of earthquakes, the dynamic behavior of reinforced concrete structures will unavoidably be nonlinear or inelastic. Even the structures equipped with vibration control devices may enter the plastic domain. Therefore, there is a need to develop new programs, or enhance existing programs, that have capabilities to perform both types of analysis to make it be able to analyze the control problem of nonlinear structures.

OpenSees (PEER) computational platform is unique in this regard, in that it offers an integrated environment for finite element analysis and handles control problem using scripting language Tcl/Tk wrapped in OpenSees. In this study, an effort is made to develop a methodology to include structural control problem into the finite element analysis. A nonlinear control approach is employed for conducting the control problem in OpenSees platform. Such control algorithm does not require the exact knowledge of a mathematical model of the plant and only some previously known expert knowledge of the subsystem is needed to develop the fuzzy controller, in that it can be integrated into OpenSees platform. A two-story reinforced concrete (RC) frame equipped with magneto-rheological (MR) dampers is constructed and employed to perform shaking table tests. The aforementioned control scheme is used to command the MR damper. Comparison between the response of the test structure and the numerical model is performed to demonstrate the feasibility and effectiveness of the proposed methodology.

9057-89a

Mathematical modeling and numerical simulation of an actively stabilized beam column with circular cross section

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Buckling of axially loaded beam columns represents a critical design constraint for light-weight structures. Besides passive solutions to increase the critical buckling load, active buckling control provides a possibility to stabilize slender elements in truss-structures. So far, buckling control by active forces or bending moments has been mostly investigated for beam columns with rectangular cross sections and with a preferred direction of buckling. The proposed approach investigates active buckling control of a beam column with circular solid cross section which is clamped at its base and pinned at its upper end. Three controlled active forces are applied near the clamped base in 120° angles to each other to stabilize the beam column and allow higher critical axial loads. The system behavior is simulated using a finite element model of the structure consisting of 3D beam elements with six degrees of freedom at each node. Two independent modal state space systems are derived for the bending planes in the lateral y- and z-directions of the circular cross section. These are used to design two linear-quadratic regulators (LQR) that determine the necessary control forces which are transformed into the directions of the applied forces. The beam column is subject to a static axial load and lateral disturbance forces with varying directions and offsets. Furthermore, a predeflection of the beam column can be included so that the critical uncertainties in buckling are considered. With the described control it is possible to actively stabilize the structure for axial loads significantly above the critical buckling load which shows the effectiveness of the investigated concept.

9057-90a

Piezogenerator impedance matching using Mason equivalent circuit for harvester identification

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This paper presents an optimization approach to piezogenerator circuit for piezo-based harvester. Most of the optimization method is tuning the impedance to reach maximum power output at resonance frequency. We give another way to model the piezogenerator to a equivalent circuit. With this equivalent circuit which could be obtained from harvester identification, it is easy to find the optimal impedance and possible to find a constant-like power output with suitable impedance.

This optimization approach uses Mason Equivalent Circuit to model a piezogenerator. Then the Mason Equivalent Circuit could be equivalent to a circuit contains capacitance paralleled with series RLC circuit. By connecting equivalent circuit and the load, the whole equivalent circuit model for harvester is built up. Single mode system is used to describe the piezogenerator, which is imposed by constant sinusoid force. By impedance matching, optimal impedance is found for (a) purely resistance load and (b) inductance with resistance load. For case (a), maximum power is depending not only on the coupling factor but also the excitation frequency. For case (b), maximum power could keep constant whatever the excitation frequency is. In practice, only the harvester identification for a equivalent circuit is required. Then all the optimal parameters could be solved. Karush-Kuhn-Tucker conditions method (KKT method) is another piezo harvester optimization method. Compared with sophisticated KKT method, the approach proposed here is easy to implement and requires solving quartic equation at most. The value of electrical components can not always meet the requirement of optimization precisely. This “precise problem” also affects the optimization effect.

9057-91a

A simplified evaluation and design procedure for frame buildings with viscous dampers based on probability of collapse

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This paper describes development of a simplified procedure for estimating the seismic sidesway collapse capacity of frame building structures incorporating linear and nonlinear viscous dampers. The proposed procedure is based on replacing a multi-degrees-of-freedom (MDOF) structural system with viscous dampers by a fictitious viscously damped single-degree-of-freedom (SDOF) system characterized by a bilinear relationship between the lateral force and roof displacement obtained from pushover analysis. The collapse level spectral acceleration associated with the resulting nonlinear SDOF system is then quantified by utilizing the developed parameters from a robust database of SDOF responses obtained from 400 million nonlinear time history dynamic analyses. The procedure is outlined with corresponding steps, and its effectiveness is demonstrated by comparing the collapse capacity predictions on 1190 different building models with those obtained from incremental nonlinear dynamic analyses. A straightforward design procedure is also developed for frame buildings incorporating viscous dampers based on achieving a pre-determined probability of collapse under maximum considered earthquake (MCE) ground motions. Given the inherent simplicity and paralleled consistency with current methodologies used in seismic design practice, the proposed procedure represents a useful and efficient tool for practicing engineers and researchers interested in evaluating the safety of frame structures with viscous dampers against seismic sidesway collapse and for designing new buildings with minimal computational overhead.

9057-92a

A comparison between non linear control logics applied to a 3-segments manipulator

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Non-linear behavior is present in many mechanical system operating conditions, especially if non-small oscillations are considered. In these cases, in order to improve the vibration control performances achievable with the linearization of the equations of motion in a given equilibrium point, a common engineering custom is to design the control system for a set of linearized models, in certain operating conditions. Then the gain-scheduling allows to change the parameters of the control law according to the current working condition increasing the system stability too. However more recently new control logics directly applicable to the systems in non-linear form, such as the sliding-mode control, have been developed. The aim of this paper is to present a nonlinear control system and to compare its performances with the standard linearized approaches. In particular a smart boom formed by three carbon fiber flexible segments and actuated by three electrical motors is chosen to test the proposed logics. The numerical simulations are carried out through a co-simulation between the MSC/Adams and the MATLAB/Simulink commercial software. At the beginning a system identification technique to define the state space model for the gain-scheduling and the nonlinear model for the sliding-mode is applied. Then the control laws for the nonlinear motion of the structure are tested on different system movements.

9057-93a

Photoresponsive polymer design for solar concentrator self-steering heliostats

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Concentrating solar energy and transforming it into electricity is clean, economical and renewable. One design of solar power plants consists of an array of heliostats which redirects sunlight to a fixed receiver tower and the generated heat is converted into electricity. Currently, the angles of elevation of heliostats are controlled by motors and drives that are costly and require diverting power that can otherwise be used for producing electricity. We replace the motor and drive system of the heliostat with a photosensitive polymer design that can tilt the mirror using the ability of the polymer to deform when subjected to light. The light causes their molecular structure to kink and subsequently, the polymer deforms. The deformation of the polymer is quantified using photostrain. A mathematical model is derived governing the behavior of the angle of elevation as the photostrain varies. Photostrain depends on the composition of the polymer, intensity and temperature of light and angle of light polarization. Preliminary findings show a photomechanical rod structural design can provide 60 degree elevation for temperatures of about 40C. A photomechanical beam structural design can generate more tilt at lower temperatures. Photostrains on the order of 1% to 10% are desired for both rod and beam designs to produce sufficient tilt under most conditions.

9057-94a

Numerical assessment of seismic performance of steel building with recentering damper under near-fault ground motions

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The seismic performance of steel building with recentering damper-based energy dissipation system under near-fault ground motions are numerically investigated in this paper. An innovative hybrid shape memory alloys friction damper, possessing both large energy dissipation and re-centering capabilities, was developed and tested. A simulation program based on MATLAB software was presented and nonlinear analysis of a three-story steel frame with and without the dampers subjected to a number of representative near-fault ground motions were performed. The results show the damper has both the stable energy dissipating capacity and re-centering feature under reverse loading and is effective in reducing the seismic response of steel building exited by strong near-fault ground motions.

9057-95b

Multi-objective optimal design of magnetorheological engine mount based on an improved non-dominated sorting genetic algorithm

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A novel flow-mode magneto-rheological (MR) engine mount integrated a diaphragm de-coupler and the spoiler plate is designed and developed to isolate engine and the transmission from the chassis in a wide frequency range and overcome the stiffness in high frequency. A lumped parameter model of the MR engine mount in single degree of freedom system is further developed based on bond graph method to predict the performance of the MR engine mount accurately. The optimization mathematical model is established to minimize the total of force transmissibility over several frequency ranges addressed. In this mathematical model, the lumped parameters are considered as design variables. The maximum of force transmissibility and the corresponding frequency in low frequency range as well as individual lumped parameter are limited as constraints. The multiple interval sensitivity analysis method is developed to select the optimized variables and improve the efficiency of optimization process. An improved non-dominated sorting genetic algorithm (NSGA-II) is used to solve the multi-objective optimization problem. The synthesized distance between the individual in Pareto set and the individual in possible set in engineering is defined and calculated. A set of real design parameters is thus obtained by the internal relationship between the optimal lumped parameters and practical design parameters for the MR engine mount. The program flowchart for the improved non-dominated sorting genetic algorithm (NSGA-II) is given. The obtained results demonstrate the effectiveness of the proposed optimization approach in minimizing the total of force transmissibility over several frequency ranges addressed.

9057-96b

Control of 4-DOF MR haptic master for medical application

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In this work, MR haptic master for minimally invasive surgery (MIS) is proposed and analyzed. Using a controllable MR fluid, the masters can generate a reflection force with the 4-DOF motion. The proposed master consists of two actuators: MR clutch featuring gimbal mechanism for 2-DOF rotational motion (X and Y axes) and MR clutch attached at gripper of gimbal structures for 1-DOF rotational motion (Z axis) and 1-DOF translational motion. After analyzing the dynamic motion by integrating mechanical and physical properties of the actuators, torque model of the proposed haptic master is derived. In order to generate an objective force, optimization procedure based on finite element analysis is conducted. The purpose of optimal design is to find the optimal geometric dimensions of the MR clutch structures that can generate maximum reflection force with restricted dimensions. Then, with determined parameters, the MR haptic master is manufactured. For realization of master-slave MIS system, an encoder is integrated with the MR spherical joint to establish the MIS master system. In this work, slave and organ of patient is modeled in virtual space. In order to embody a human organ into virtual space, a volumetric deformable object is mathematically formulated by a shape retaining chain linked (S-chain) model. Accordingly, the haptic architecture is established by incorporating the virtual slave with the master device in which the reflection force and desired position originated from the object of the virtual slave and operator of the master, respectively, are transferred to each other. In order to achieve the desired force trajectories, a sliding mode controller (SMC) is designed and implemented. It has been demonstrated that the effective tracking control performance for the desired motion of reflection force is well presented in the time domain.

9057-97b

Design and characteristics of MRF-based actuators for torque transmission under influence of high shear rates up to 10,000s-1

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Actuators based on magnetorheological fluids (MRF) for torque transmission experience a growing interest for the application in the field of electric drive technology and also in automotive technology due to their outstanding properties e.g. the smooth adjustable torque, the fast response time and the noiselessness. In these industries, demand for increasingly higher braking-power densities and maximum rotational speeds is gradually outpacing the performance capabilities of

conventional electromagnetic brakes and clutches in terms of wear or overheating effects. By using MRF-based actuators with a scalable fluid volume for torque transmission, new technical capabilities can be opened up. With the appropriate design of the fluidic system of an MRF brake or clutch, additional dissipated energy and thermal load peaks can be tolerated due to their inherently larger shear gap volumes relative to the thin contact surface found in conventional friction-based systems.

The challenges to meet are high rotational speeds up to 6,000min-1. By an adequate design of the shear gaps, fluid flow states like a developing Taylor-Couette flow can be used to ensure a stable operation even in the critical idle mode at high rotational speeds when no magnetic field is applied and the fluid is exposed to different forces caused by accelerating fields such as gravity, centrifugal forces and inertial force. A critical separation of particles due to the high differences in the density of the MRF components carrier fluid and carbonyl iron powder particles can be avoid by the Taylor-Couette flow. Depending on the dimension of the shear gaps, very high shear rates up to 10,000s-1 and more can occur. Measurements with actuators for torque transmission at such high shear rates show an undesired decrease of the transferred torque or respectively yield stress at a higher level of magnetization in an amount up to 30%.

In the final paper, the design of MRF-based actuators for torque transmission at high rotational speeds will be considered. Theoretical considerations of the developing flow profiles will be discussed and design rules for MRF-based actuators for the use at high rotational speeds are introduced. A special focus is given on the investigation of the torque decrease at high shear rates and magnetization. A modeling approach based on a micromechanical particle model will be introduced to describe this characteristic. Measurements with a realized actuator will validate the theoretical considerations and underline the characteristic of MRF-based actuators for torque transmission under the influence of high rotational speeds up to 6,000min-1 or respectively high shear rates up to 10,000s-1 and more.

9057-98b

A flexible magnetically field-controllable fluid transport system

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This study presents the magnetic-fluid-structure interaction in a soft isotropic magnetorheological elastomer (MRE)-based fluid transport system. The system consists of a MRE tube, flexible valves within the tube, a fluid flowing through the tube, and a magnetic field which interacts with the MRE-based tube. This system may have bio-inspired applications such as augmentation or replacement of damaged lymphatic vessels. Magnetics, elasticity and fluid dynamics are coupled to investigate the deflection of this magnetically actuated MRE system can propel fluid. Two and three-dimensional time-dependent models using magnetic-fluid-solid interaction and arbitrary Lagrangian - Eulerian moving mesh method are implemented. Results demonstrate fluid propulsion capabilities of the proposed system. The effects of magnetic field fluid properties and transport system structural properties on the flow rate are studied.

9057-99b

Application fuzzy neural network control algorithm to a seismically isolated bridge using magneto-rheological damper

Yong-Quan Ma, Hong-Xing Qiu, Southeast Univ. (China)

In order to solve the problems which bearings and girder displacements of isolated bridges is too large after seismic, taking the three-span highway continuous girder bridges isolated by LRB for the engineering example, use the magneto rheological damper (MRD) as control device, the neural network is employed to identify the dynamic characteristics of the full-scale MRD, the fuzzy neural network strategy which is suitable to MRD and based on the theory of zoning control is proposed, the numerical simulation are carried out for analyzing the nonlinear seismic responses of the engineer ing example and non-isolated bridge with MRD, and the simulation results are compared with those of LQG active control systems. The consequences indicate that the developed semi-active controller had good performance, which could reduce the bearings and girder displacements of isolated bridges, could also reduce the any seismic response in the non-isolated bridges caused by strong earthquakes; the control force time history curve of semi-active control algorithm in good agreement the curve of LQG active control algorithm, it could prove that the intelligent semi-active controller had a good potential in the control of nonlinear vibrations of bridges.

9057-100b

Prosthetic leg powered by MR brake and SMA wires

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Current prosthetic legs rely on electric motors for both moving and stationary states. The electric motors draw an especially high level of current to sustain a fixed position. The advantage of using MR fluid is that it requires less current and can have a variable braking torque. Besides, the proposed prosthetic leg is moved by NiTinol wire, a popular shape memory alloy (SMA). The incorporation of NiTinol gives the leg more realistic weight distribution with appropriate arrangement of the batteries and wires.

The prosthesis in this research was designed with MR brake as stopping component and SMA wire network as actuating component. The MR brake was designed with novel shape for the rotor that improved the braking torque while minimizing the power consumption. The design also helped simplify the control of braking process. The SMA wire network was design so that the knee motion was actively rotated in both directions. The SMA wires was arranged and played very similar role as the leg's muscles. The study started with the overall solid design of the knee including both MR and SMA parts. Theoretical models were derived and programmed in Simulink for both components. The simulation was capable of predicting the power required for moving the leg or hold it in a fixed position for a certain amount of time. Subsequently, the design was prototyped and tested to validate the theoretical prediction. The theoretical models were updated accordingly to correlate with the experimental data.

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9058-1

Fracture toughness enhancement due to global thermo-mechnically-induced phase transformation in shape memory alloy actuators *(Invited Paper)*

Dimitris C. Lagoudas, Sameer Jape, Theocharis Bexevanis, Texas A&M Univ. (United States)

Shape Memory Alloys (SMAs) can recover large, apparently permanent, strains when subjected to particular thermomechanical inputs. The key physical mecha- nism that drives this shape recovery is a reversible diffussionless solid to solid phase transformation from austenite to martensite and vice-versa under applied load or temperature variations. SMA actuators take advantage of this property to provide a significant amount of actuation with an extremely small envelope volume.

In this work, the effect of thermo-mechanically-induced global phase transfor- mation on crack growth in an SMA actuator is investigated by means of the finite element method. The prototype center-crack problem is analyzed during thermal cycles under isobaric loading conditions. The temperature variation is sufficient to induce global phase transformation. The virtual crack closure technique is em- ployed to measure the crack tip energy release rate during the entire actuation cycle. Results show that during actuation the energy release rate can increase drastically, an order of magnitude for specific material systems. This in turn implies that crack growth may be triggered as a result of phase transformation, resulting eventually in the actuators ultimate failure. Stable crack growth is initially observed, i.e., the resistance to fracture increases with growing crack size, however, the observed toughness enhancement associated with crack advance cannot prevent ultimate fail- ure for more than a few thermal cycles after initiation of crack propagation.

9058-2

Modeling size effect in the SMA response: a gradient theory

Majid Tabesh, James G. Boyd IV, Dimitris C. Lagoudas, Texas A&M Univ. (United States)

For sufficiently small dimensions, the response of shape memory alloy actuators is not independent of the sample size. The response of the SMA single crystal micro/nano pillars, for instance, is shown to depend on the size of the specimen, with an increase in the critical stresses for the start and finish of austenite to martensite transformation by reducing the diameter and going to the submicron region. Also, the damping observed in a pseudoelastic cycle is much higher than that of a counterpart SMA bulk specimen. This phenomenon is furthermore observed in SMA wires. The critical stresses for the start of martensite and austenite transformations are reported to increase for diameters below 100 ?m. Such a behavior cannot be simulated using conventional constitutive theories, which lack an intrinsic length scale in their constitutive modeling. To enable the size effect, a new thermodynamically consistent constitutive model is developed, that in addition to conventional internal variables of martensitic volume fraction and transformation strain, contains the spatial gradient of martensitic volume fraction as an internal variable. This allows the introduction of a length scale in the model. The transformation surface in such a theory will be obtained from the solution of a partial differential equation; on the contrary, transformation surface in conventional theories is an algebraic equation. The developed gradient theory, in a simplified 1D fashion, is used to analytically simulate bending and torsional response of SMA beams and rods. The response of the SMA structures depends on the size, beam thickness or rod diameter, being stiffer for smaller dimensions.

9058-3

Iterative calibration of a shape memory alloy constitutive model from 1D and 2D experimental data using optimization methods

Darren J. Hartl, William D. Whitten, Texas A&M Univ. (United States)

Shape memory alloy constitutive models have been shown to accurately predict 1-D and 3-D material response under general thermomechanical loading. As with any constitutive model, however, the degree to which simulation results match experimental data is dependent on the accurate calibration of model parameters. This work presents a general framework for the identification of SMA material parameters using numerical optimization methods and experimental results that include both 1-D data (i.e., stress-strain and strain-temperature line plots) as well as 2-D digital image correlation (DIC) strain field data. Multiple optimization algorithms and fitness function definitions are considered and their effectiveness and efficiency are compared in calibrating ~10 parameters simultaneously. The optimization framework is first verified using 1-D and 3-D finite-element-based simulated results as pseudo-experimental data. Effective calibration is then demonstrated using experimental data taken from both conventional testing and digital image correlation considering both isobaric and pseudoelastic tests. The study shows that the proposed optimization methods can identify SMA parameters in an automated fashion using data taken from multiple types of experiments and provide more accurate results than traditional calibration methods.

9058-4

Three-dimensional constitutive model considering transformation-induced damage and resulting fatigue failure in shape memory alloys

Darren J. Hartl, Texas A&M Univ. (United States); Yves Chemisky, Fodil Meraghni, Lab. d’Etude des Microstructures et de Mécanique des Matériaux (France)

In this work, a constitutive model is developed that describe the behavior of shape memory alloys undergoing a large number of cycles, developing internal damage, and eventually failing. Physical mechanisms associated with martensitic phase transformation occurring during cyclic loadings such as transformation strain generation and recovery, transformation-induced plasticity, and fatigue damage are all taken into account within a thermodynamically consistent framework. Fatigue damage is described utilizing a continuum theory of damage. The damage growth rate has been formulated as a function of both the stress state and also the magnitude of the transformation strain, while the complete or partial nature of the transformation cycles is also considered as per experimental observations. Simulation results from the model developed are compared to uniaxial actuation fatigue tests at different stress levels. It is shown that both lifetime and the evolution irrecoverable strain can be accurately simulated.

9058-6

Interfacial stress in shape memory alloy reinforced polymer composites

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Debonding of Shape Memory Alloy (SMA) wires in SMA reinforced polymer matrix composites is a complex phenomenon compared to other passive fibre debonding in similar matrix composites. This paper focuses on computational and experimental study of stress required for debonding of thermal SMA actuator wire reinforced composites. Fibre pull-out test are carried out on thermal SMA actuator at patent state by stress induced detwinned martensites. An ASTM standard is followed as benchmark method for fibre pull-out test. A reduced order one-dimensional finite element model is developed wherein the SMA constitute model is coupled with elasto-plastic epoxy material model. Debonding stress is derived with the help of non-local shear-lag theory applied to elasto-plastic interface. Furthermore, experimental investigations are carried out to study the effect of Laser shot peening on SMA surface to improve the interfacial strength. Variation in debonding stress due to length of SMA wire reinforced in epoxy are investigated for peened and non-peened SMA wires. Simulation and experimental results of interfacial strength variation due to various pre-stress while applying two-way transformation of the thermal SMA actuator wires in epoxy matrix are discussed.

9058-7

Hierarchical multifunctional nanocomposites

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Nanocomposites; including nanomaterials such as carbon nanotubes (CNTs) and graphene nanosheets (with dimensions less than 100 nm, i.e., the range where the phenomena associated with the atomic and molecular interaction strongly influence the macroscopic properties of materials) are of significant importance in the rapidly developing field of nanotechnology. Due to the nanometer size of these inclusions, their physicochemical characteristics differ significantly from those of micron size and bulk materials. Nanomaterials have enormous surface areas that influence the interface/interphase regions. By contrast, a conventional composite with micrometer size inclusions have a much smaller surface-to-volume ratio, and hence influence the properties of the host structure to a much smaller extent. The optimum amount of nanomaterials in the nanocomposites depends on challenging parameters such as nanomaterials size, shape, homogeneity, distribution, and the interfacial bonding properties between the constituents. The promise of nanocomposites lies in their multifunctionality. The properties of the matrix/resin can be improved by the inclusions of nanomaterials (Nanoresin). The properties of the fibers can also be improved by the growth of CNTs on the fibers (Nanoforest). The combination of the two will produce super-performing nanocomposites, not currently available. Since this process involves the production of nanometer CNTs on micro fibers to give micro-composites, this process is a bottom-up "hierarchical" advanced manufacturing process, and since the resulting nanocomposites will have "multifunctionality" with improve properties in various functional areas, the resulting nanocomposites are in fact "hierarchical multifunctional nanocomposites." Here, the current state of knowledge in processing, performance, and characterization of these materials are addressed.

9058-8

Multifunctional composites for energy storage

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Electrochemical super-capacitors have become one of the most important topics in both academia and industry as novel energy storage devices because of their high power density, long life cycles, and high charge/discharge efficiency. Recently, there has been an increasing interest in the development of multifunctional structural energy storage devices such as structural super-capacitors for applications in aerospace, automobiles and portable electronics. These multifunctional structural super-capacitors provide lighter structures combining energy storage and load bearing functionalities. Due to their superior materials properties, carbon fiber composites have been widely used in structural applications for aerospace and automotive industries. Besides, carbon fiber has good electrical conductivity which will provide lower equivalent series resistance; therefore, it can be an excellent candidate for structural energy storage applications. Hence, this paper is focused on performing a pilot study for using nanowire/carbon fiber hybrids as building materials for structural energy storage materials; aiming at enhancing the charge/discharge rate and energy density. This hybrid material combines the high specific surface area of carbon fiber and pseudo-capacitive effect of metal oxide nanowires which were grown hydrothermally in an aligned fashion on carbon fibers. The aligned nanowire array could provide a higher specific surface area that leads to high electrode-electrolyte contact area and fast ion diffusion rates. Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) measurements were used for the initial characterization of this nanowire/carbon fiber hybrid material system. Electrochemical testing has been performed using a potentio-galvanostat. The results show that gold sputtered nanowire hybrid carbon fiber provides 65.9% better performance than bare carbon fiber cloth as super-capacitor.

9058-9

Design of a multifunctional composite material with enhanced structural and power storage capability

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The paper presents results related to the electromechanical characterization of a carbon fiber based composite material with power storage capabilities. Particular attention is give to the effect of different coatings applied on the carbon fiber weave that acts as an electrode in this material construct. While the coatings, generally, enhance the specific capacitance of the material, they cause a deterioration of the leakage resistance and equivalent series resistance of the material. The mechanical properties tend to be enhanced by all the coatings tested.

9058-10

3D jet printer of edible gels for food creation

Ryo Serizawa, Mariko Shitara, Kouki Yamamoto, Jin Gong, Masato Makino, Md. Hasnat Kabir, Hidemitsu Furukawa, Yamagata Univ. (Japan)

In recent years, aging is progressing in Japan. Elderly people can't swallow the food well. So, the need of soft food is increasing greatly with the aging of the population. There are so few satisfying foods for the elderly to enjoy a meal. An equipment of printing delicious food gives the elderly a big dream and is promising. In this study, we aim at developing a 3D edible gel printer in order to make tasty soft food. We made a prototype of the 3D edible gel printer. The printer consists of syringe pump and dispenser. The syringe pump extrudes the solution. The dispenser allows to model three-dimensional objects. We use agar solution as the ink to carry out the printering. Agar's gelation deeply depends on temperature. Therefore temperature control of the solution is important to mold optimal shapes because the physical crosslinking

network of agar's solution is instability. We succeeded in making the gels and plate-shape gel using the 3D edible gel printer. Further more, in order to increase the gelation speed agar's solution, we changed the dispenser and the printing test is being done now. Few bubbles were found in the printed agar palate. In the future, the viscosity of the agar solution or other food ink should be adjusted to suitable for printing.

9058-11

Fabrication and characterization of a foamed polylactic acid (PLA)/ thermoplastic polyurethane (TPU) shape memory polymer (SMP) blend for biomedical and clinical applications

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Shape memory polymers (SMP) are a class of responsive stimuli materials that are able to respond to external stimulus such as temperature and deformation by altering their shape, and return to their original shape upon reversal or removal of the external stimulus. Bio-compatible SMPs are especially of interest for biomedical and clinical applications (e.g. stents and scaffolds). A previous study has demonstrated that the bio-compatible polymer blend of polylactic acid (PLA)/ thermoplastic polyurethane (TPU) exhibit good shape memory properties. In this study, we characterize the foamed properties of this PLA/TPU SMP blend. The PLA/TPU bio-compatible SMP blend was fabricated by melt-blending and gas foaming. The various shape memory and mechanical properties of the foam and solid PLA/TPU SMP blends were studied and compared; these properties include: strain fixity, strain recovery, time response, blocking force, stress-strain response, and tensile and compression strength. The morphology of the foam structure was studied with scanning electron microscopy (SEM). The foam PLA/TPU SMP blend was found to have improved compression strength and lighter weight compared to the solid polymer blend. In addition, the foamed structure is able to absorb impact, which also makes it suitable for applications where damping is required.

9058-12

Frictional properties of gel engineering materials with laser surface texturing

Naoya Yamada, Jin Gong, Masato Makino, Md. Hasnat Kabir, Keisuke Maekawa, Masato Wada, Hidemitsu Furukawa, Yamagata Univ. (Japan)

Several synthesis methods have been devised to improve the mechanical strength of gels extraordinarily after 2001. It was a trigger to use gels as a new industrial materials, since gels had been considered difficult for industrial materials because of their weakness. In a recent study, we had designed transparency shape memory gels for the first time. Shape memory gels are one of the gels with characteristic networks, and have a shape memory function by copolymerizing an acrylic monomer with a hydrophobic long alkyl side group. It is well known that the mechanical properties such as Young's modulus and friction coefficient of shape memory gels depend on temperature.

In this study, we tried to change the frictional properties of shape memory gels by laser surface texturing. Two types of processed surface were prepared. The hexagonal close packed pattern and the square close packed pattern of dimples were formed on the surface of gel sheets with CO2 laser. The intensity of laser was optimized to avoid cutting gels. The friction coefficients of unprocessed gels and two types of processed gels were measured by ball-on-disk method. Measurement partner material was soda-lime glass ball. The measurement results of processed gels showed clear differences from unprocessed gels. The friction coefficients of processed gels were larger than unprocessed gels. However, these results specifically showed the velocity dependence. It indicates that surface texturing enable to control the friction coefficient of polymer gels by surface pattern and velocity.

9058-13

Frictional properties of high functional gel materials

Masato Wada, Kohei Yamada, Naoya Yamada, Masato Makino, Jin Gong, Hidemitsu Furukawa, Yamagata Univ. (Japan)

Gels are new materials, not so hard and dry as metals, ceramics, and plastics, but soft and wet as the human body. Gels have superior properties such as high water content, material permeability, especially low friction and biocompatibility, which are not found in hard and dry materials, because these properties are due to their soft and wet features. The frictional behavior of the two kinds of high-strength gels, which were double network (DN) gels and shape memory gels (SMG), was studied. By using a commercial measuring instrument with an empirical fitting function, the coefficient of dynamical friction for the DN gels and the SMG was determined. The velocity dependence of the coefficient looked roughly similar for both the DN gels and the SMG, however the details of the dependence were different. The coefficient of the DN gels was smaller than that of the SMGs. The coefficient decreased as the normal force increased. This normal force dependence was observed for the DN gels previously, however for the first time for the SMGs. The differences of both the velocity and normal-force dependences between the DN gels and SMG were discussed in relation to their mechanical properties determined in the previous studies. It implied that the difference of the dependences was possibly related to the different softness of the gels. The difference of the dependences is possibly related to the different softness by the temperature change of the gels. Therefore, we show a coefficient of friction by the temperature change of the SMG.

9058-14

Facile fabrication of uniaxial nanopatterns on shape memory polymer substrates using a complete bottom-up approach

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In earlier work, we have demonstrated a fabrication method of nanosized unidirectional wrinkles on PDMS/SMP bi-layer structures using a complete bottom-up approach. The method starts with using self-assembled Al/SMP wrinkled surface as the template to make a replica of surface wrinkles on a PDMS layer which is spin-coated on a pre-programmed SMP substrate. When the shape recovery of the substrate is triggered by heating it to its transition temperature, the substrate shrinks uniaxially to return to its permanent shape. Consequently, the wrinkle wavelength on PDMS reduces accordingly. A subsequent contact molding process is carried out on the PDMS layer spin-coated on another SMP substrate, but using the wrinkled PDMS surface obtained in the previous step as the master. By activating the shape recovery of the substrate, the wrinkle wavelength is further reduced a second time. A series of such recursive contact molding cycles, in which the wavelength-reduced patterned substrate from each cycle serves as the template for the next one, can monotonically reduce the original wrinkle wavelength to the desired range. We have showed that the starting wavelength of 640 nm decreased to 290 nm after two cycles of recursive molding. In this work, we further improve the results to challenge the top-down fabrication techniques represented by lithography. Wrinkle wavelength has a further significant reduction. In addition, they are fabricated on substrates larger than a Si wafer. The present study is expected to offer a simple and cost-effective large-area fabrication method of nano-scale uniaxial wrinkle patterns with the potential for large-scale mass-production.

9058-15

Designing light responsive bistable arches for rapid, remotely triggered actuation

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Light responsive azobenzene functionalized polymer networks enjoy several advantages as actuator candidates including large deformations, the ability to be remotely triggered, in some cases the ability to be photo fixed, and highly tunable control via light intensity, polarization, wavelength and material alignments. One significant challenge hindering these materials from being employed in applications is their often relatively slow actuation rates and low power densities, especially in the absence of photo-thermal effects. One well known strategy employed in nature for increasing actuation rate and power output is the storage and quick release of elastic energy (e.g., the Venus flytrap). Using nature as inspiration we have conducted a series of experiments and developed an equilibrium mechanics model for investigating remotely triggered snap-through of bistable light responsive arches made from GPa-modulus azobenzene functionalized polymers. These systems require only low irradiation intensities (<<100mW/cm2) to produce actuation rates approaching 100mm/s and power densities of approximately 1kW/m3. After briefly discussing experimental observations we consider in detail a geometrically exact, planar rod model of photomechanical snap-through. The theoretical energy release characteristics and unique strain field profiles provide insight toward design strategies for improved actuator performance. The bistable light responsive arches presented here are potentially a powerful tool for producing remotely triggering rapid motion from apparently passive structures in applications such as binary optical switches and positioners, surfaces with morphing topologies, and impulse locomotion in micro or millimeter scale robotics.

9058-16

Development of a standard method to observe the surface friction of high-strength gels

Kouhei Yamada, Naoya Yamada, Yosuke Watanabe, Masato Wada, Jin Gong, Masato Makino, Md. Hasnat Kabir, Hidemitsu Furukawa, Yamagata Univ. (Japan)

In the last decade, several innovative ways to enhance the mechanical properties of polymer gels have been proposed. In 2003, the most effective but simple way was proposed to synthesize double network gels, whose compression fracture stress reached about 30MPa, while that of common gels is several tens kPa. Our group has focused on PAMPS-PDMAAm DN gel, because it possibly has both biocompatibility and permeability, which are good for developing artificial articular cartilage and artificial blood vessel. Also it is possibly used for rapid additive manufacturing with 3D gel printer. 1st network of this gel has an electric field response, the contraction due to moisture reduction at the positive electrode side moisture inside the gel moves to the cathode side and a voltage is applied by attaching electrodes to the gel, and swelling due to moisture increase at the cathode side there is a nature to cause, is to bend to the positive electrode side. There is fun as a controllable electric field gel material from these things.

Here we develop a novel apparatus of the ball on disk method to observe the surface friction of the DN gels. In addition, the friction behavior of the gel shows behavior unlike the solid friction behavior. We hope to apply this apparatus for various studies about the tribological behavior of the gels, especially about the effect of external electric field on the gel friction. Our final goal is the control of the gel friction by the external fields.

9058-17

Modeling of ferroelectric-ferromagnetic composites to improve magnetoelectric coupling and durability *(Invited Paper)*

Andreas Ricoeur, Artjom Avakian, Roman Gellmann, Univ. Kassel (Germany)

Magnetoelectric (ME) coupling is an inherent property of only a few crystals exhibiting very low coupling coefficients. On the other hand, structures showing this effect are desirable due to many promising applications. Among these, efficient data storage devices or applications in sensors shall be mentioned exemplarily.

Efficient coupling of magnetic and electric fields in materials can only be achieved in composite structures. Here, ferromagnetic (FM) and ferroelectric (FE) phases are combined e.g. including FM particles in a FE matrix or embedding fibers of the one phase into a matrix of the other. The ME coupling is then accomplished indirectly via strain fields. Embedding e.g. particles of CoFe2O4 into a BaTiO3 matrix and imposing a magnetic field leads to a deformation of the particles due to magnetostriction. The related strain of the matrix, on the other hand, induces an electric field due to the piezoelectric effect.

The paper presents the basics and some results of Finite-Element (FE) modeling of the behavior of a ME particle composite under electrical or magnetical loading. Nonlinear ferroelectric and ferromagnetic constitutive equations are implemented within the framework of a multifield FE approach. The simulation of the poling process in terms of ferroelectric and ferromagnetic poling reveals both the efficiency in terms of coupling coefficients and mechanical stresses induced in the composite due to domain wall motion. The latter is decisive for the durability of the system. Different poling regimes lead to different outcomes and thus to more or less favorable systems. Finally, different homogenization schemes are discussed evolving effective ME constants, which are compared with experimental data.

9058-18

Mechanosensitive droplet interface bilayer networks

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A method for studying the coupled electrical-mechanical response of droplet interface bilayers is proposed. This research examines the concept of the biologically-inspired hair cell in greater depth, attempting to determine the source of the sensing current when no external potential is applied across the sensing droplet-interface bilayer element. Historically the mechanosensitive current in these droplet-interface bilayers has been attributed to a combination of capacitive currents and electrode oscillation (experimental error); however the development of a third sensing mechanism through modifying the bilayer properties may enhance the usefulness of the mechanosensitive droplet interface bilayer networks considerably. This would allow for measurable sensing currents without requiring an externally applied electric field by permanently charging the bilayer element through surface modifications.

Charging agents are added to the droplet interface bilayer network as the network is oscillated and the electrical response is recorded for analysis. The adsorption of the charged molecules is studied through the intramembrane field compensation (IFC) approach, and the knowledge gained from this is then applied towards the mechanosensitivity analysis. Multiple charging techniques are tested and employed, and the nature of the sensing current is determined byexamining the frequency content of the recorded currents. Several properties are derived, including the nature of the sensing current, the charging mechanisms available for boosting the sensing current, and the nature of the sensing current without externally applied potentials.

9058-58

Characterization of optically actuated MRI-compatible active needles for medical interventions

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The development of a Magnetic Resonance Imaging (MRI) compatible optically-actuated active needle for guided percutaneous surgery and biopsy procedures is described. Electrically passive MRI-compatible actuation in the small diameter needle is provided by non-magnetic materials including a shape memory alloy (SMA) subject to precise optical fiber laser operation that can be from a remote (e.g., MRI control room) location. Characterization and optimization of the needle is facilitated using optical fiber Bragg grating (FBG) temperature sensors arrays. Active bending of the needle during insertion allows the needle to be accurately guided to even relatively small targets in an organ while avoiding obstacles and overcoming undesirable deviations away from the planned path due to unforeseen or unknowable tissue interactions. This feature makes the needle especially suitable for use in image-guided surgical procedures (ranging from MRI to CT and ultrasound) when accurate targeting is imperative for good treatment outcomes. Such interventions include reaching small tumors in biopsies, delineating freezing areas in, for example, cryosurgery and improving the accuracy of seed placement in brachytherapy. Particularly relevant are prostate procedures, which may be subject to pubic arch interference. Combining diagnostic imaging and actuation assisted biopsy into one treatment can obviate the need for a second exam for guided biopsy, shorten overall procedure times (thus increasing operating room efficiencies), address healthcare reimbursement constraints and, most importantly, improve patient comfort and clinical outcomes.

9058-20

Dynamic electromechanical behavior of barium titanate cantilevers under ac electric fields

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We discuss the dynamic electromechanical behavior of barium titanate (BT) unimorph cantilevers with sensing, grounding and driving electrodes under alternating current (AC) electric fields. A three-dimensional finite element analysis (FEA) was performed to predict the deflection and output voltage in the BT unimorph cantilevers. The deflection and output voltage were also measured, and numerical results were compared with measured values. The deflection, stress, output voltage and output power were then examined in detail.

9058-21

Geometrically nonlinear and coupled thermopiezomechanical modeling and analysis of smart composite shells

Narasimha R. Mekala, Rüdiger Schmidt, RWTH Aachen (Germany)

In recent years, the subject area of theories and finite element tools for modeling and simulation of smart structures has experienced tremendous growth in terms of research and development, especially in thin-walled structures as a specific area of the light-weight structures. Many models describing their behaviour have been developed with varying levels of simplification. In the vast majority of papers available in literature coupling of the mechanical, electrical, and eventually thermal field quantities is taken into account in the constitutive equations only. The truly coupled thermo-piezo-elastic analysis, however, does not only consider the temperature and piezoelectric effect on the strains, but accounts for the coupling effects of the mechanical, electrical and thermal quantities in the field equations.

A thermodynamically consistent continuum mechanics based framework that includes the fully nonlinear thermo-piezo-mechanical coupling effects is used. A finite element concept based on weak formulations of the conditions of equilibrium, conservation of electric charge and mechanical energy is applied. Transition from 3-D continuum mechanics to 2-D theories of plates and shells is performed in the framework of the Reissner-Mindlin hypothesis. The fully geometrically nonlinear shell theory accounts for small strains and finite rotations, as well as for the nonlinear coupling effects between the mechanical, electrical and thermal variables. Various nonlinear and coupling effects are simulated using FE-code for a piezolaminated beams, plates and shells subjected to thermal load.

9058-22

Suppression method of overshoot on non/less-energy shape-retainment control utilizing hysteretic behavior of piezoelectric actuators

Tadashige Ikeda, Tomonori Uchida, Nagoya Univ. (Japan)

To keep a shape of a smart structure controlled with piezoelectric actuators bonded on it, the electric voltage must be applied continuously. To reduce the amount of electricity usage, a new control method was proposed and its feasibility was examined in the previous studies [Proc. of SPIE 8689 86890C, Proc. of 29th ISTS 2013-c-40]. In this method hysteretic behavior of the piezoelectric actuators in strain-electric field relationship was utilized effectively, in which some amount of strain remains even at zero voltage once a large voltage is applied. The results showed that deformation of a smart beam with a piezoelectric ceramic actuator bonded remained without applying voltage to the actuators after applying a pulsed voltage. However, the deformation overshot a final position while applying the pulsed voltage. That is undesirable when high precision is required. In this paper a suppression method of this overshoot is proposed. To this end a different type of piezoelectric actuator opposing the original actuator is also bonded on the beam. The opposing actuator is a hard type and it has much less hysteresis than the original actuator of soft type within the strain range of use. Accordingly, the deformation, that is, overshoot can be suppressed while applying the pulsed voltage by controlling the voltage to each actuator adequately, yet a desired deformation can be obtained at zero voltage after the pulse. It is confirmed that this method is effective to suppress the overshoot experimentally.

9058-23

Finite element implementation of a novel strain energy function for dielectric elastomers

Austin Allen, Nakhiah C. Goulbourne, Univ. of Michigan (United States)

Dielectric elastomers (DEs) are a type of electro active polymer desirable for use as large strain sensors, actuators, and energy harvesters, but the development of simple and accurate models for the electromechanical response is ongoing in the literature. This work aims to numerically solve complex boundary value problems involving DEs by creating a user material (UMAT) subroutine for the commercially available finite element (FE) software ABAQUS®. Previously, Davidson and Goulbourne developed a physics based strain energy function which captures the large strain mechanical response of a variety of elastomers with relatively few parameters that are linked to the polymer chemistry. We decouple this strain energy function to allow for material compressibility and then

combine it with an electrostatic contribution to derive new analytical expressions for the Cauchy stress and tangent modulus tensors to be implemented in the UMAT. The results from FE simulation of a DE membrane subjected to electromechanical loading is compared with experimental data and shown to be more accurate at high strains than a Mooney-Rivlin based UMAT developed by Son and Goulbourne.

9058-24

Novel manufacturing technique for flexible hollow foamed poly(vinylidene fluoride) and the study of its piezoelectric response

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Poly(vinylidene fluoride) (PVDF) is a semi-crystalline polymer that exhibits a significantly stronger piezoelectric effect compared to other polymers. When mechanical deformation such as stretching is applied to the polymer, the polymer chain would orientate from the common TGTG structure (alpha phase) into TTTT alignment (beta phase), which exhibits a net polarization. To maximize the piezoelectric effect, recent studies have shown that parameters such as beta phase content, degree of crystallization, permittivity, and manufacturing process have a strong influence on the overall performance. Research also showed the addition of nano-material, such as multiwalled carbon nanotube (MWCNT), graphene, filler can improve the polymer electric properties dramatically. To further alter the properties of PVDF, super-critical gas foaming method maybe helpful since it increases the free volume within the sample and therefore changes the polymer chain mobility. This study presents a novel manufacturing method of thin PVDF-nanoparticle composite film by introducing super-critical carbon dioxide ($scCO_2$) batch foaming method. The physical and electrical material properties were verified using Fourier transform infrared spectroscopy (FTIR) for phase identification, differential scanning calorimetry (DSC) for percent crystallinity, scanning electron microscope (SEM) for polymer morphology, and dielectric impedance spectrometer for electrical properties.

9058-25

High energy density nanocomposite capacitors based on non-ferroelectric nanowires

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Nanocomposites containing high dielectric permittivity ceramics embedded in high breakdown strength polymers are currently of considerable interest as a solution for the development of high energy density capacitors. Compared to conventional ceramic or polymer capacitors, the nanocomposites can not only provide lightweight, compact and cost-effective devices with higher energy density capabilities, but can also be inexpensively fabricated as large and flexible devices using polymer processing techniques. The majority of current research on dielectric composites has focused on the enhancement of dielectric permittivity using high dielectric permittivity ferroelectric fillers, such as $Pb(Zr, Ti)O_3$ (PZT) and $BaTiO_3$. However, the high remnant polarization and polarization saturation of these ferroelectric ceramics leads to limited energy density. Additionally, past studies have demonstrated that the incorporation of these high dielectric permittivity fillers into composites improves the dielectric permittivity of the composites at the expense of the breakdown strength, which in turn limits the energy density of the capacitor. Therefore, the integration and geometry of the fillers must be optimized along with the filler to reach the highest possible energy density of the nanocomposites. Here, we report a method to prepare nanocomposite capacitors with a high energy density based on high aspect ratio functionalized TiO_2 NWs dispersed in a PVDF polymer. High energy density and fast discharge speed of the nanocomposite capacitor is demonstrated with the high aspect ratio NWs and high breakdown strength is observed through quenching in ice-water. The results presented here demonstrate that non-ferroelectric nanowires can be used to develop nanocomposite capacitors with high energy density and fast discharge speed for future pulsed-power applications.

9058-26

Test validation of environmental barrier coating (EBC) durability and damage tolerance modeling approach

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Protection of Ceramic Matrix Composites (CMCs) is rather an important element for the engine manufacturers and aerospace companies to help improve the durability of their hot engine components. The CMC's are typically porous materials which permits some desirable infiltration that lead to benefiting its strength. However, they experience various durability issues such as degradation which includes coating oxidation as opposed to moisture induced matrix which is generally seen at a higher temperature. Other factors such as residual stresses, coating process related flaws, and casting conditions may also affect the strength of degradation. Such defects lead to cracking and other damage which are due to not much energy is being absorbed during the fracture process.

Therefore, it is very pertinent to develop an understating of the issues that control cracking along the interfaces of coated layered ceramics to allow maximum energy dissipation capabilities. These concerns are being addressed by the introduction of a high temperature protective system, Environmental Barrier Coating (EBC) that can operate at temperature applications greater than 1100 °C [1, 3]. The EBCs are typically a multilayer of coatings and are in the order of hundreds of microns thick. This will promote the need to evaluate components and subcomponents made out of CMCs under gas turbine engine conditions to ensure that they are performing as anticipated under harsh environmental situations.

In this paper, Progressive failure lifing analysis with Genoa_Ansys-PFA-Plug-In [4] is used to evaluate conditions that would cause crack initiation in the EBC. The analysis is then coupled with fracture mechanics techniques to grow the crack to a critical size. Material properties for the EBC will be obtained from NASA testing and complemented with data from literature. The specimen will be modeled with 3 D finite elements. Based on the state of evaluated test samples, initial flaws will be incorporated in the finite element model as appropriate. Cyclic analysis will be performed to simulate test conditions whereby the temperature is ramped up from room temperature to 1300C during a period of 15 minutes then kept constant at that temperature for one hour. The specimen is then cooled down to room temperature. The analysis will determine the number of cycles the specimen sustains for crack initiation and growth. The results from the analysis will be compared to test including failure modes and failure locations, and crack length as function of number cycles. The validated analysis will establish a process for using the computational approach, validated at a specimen level, to predict reliably in the future component level performance without resorting to extensive testing.

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9058-27

Development of time-domain master curves using the data of dynamic mechanical analysis for polyurea and polyurea-based composites

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Polyurea is an elastomer which has excellent thermal-mechanical properties. In this study, we were seeking to develop a method to obtain the constitutive models of polyurea and polyurea composites that can be used for multiple computational platforms. The constitutive models were based on the experimental data of dynamic mechanical analysis (DMA). Polyurea and polyurea composites were fabricated and their storage and loss moduli were tested by DMA within a sufficiently wide temperature range above glass transition temperature and at multiple frequencies. The frequency-domain master curves were developed using the DMA data by applying time-temperature superposition (TTS). The quality of the frequency-domain master curves were accessed by Kramers-Kronig relation, and the result showed the master curves developed by TTS fit well with the causality condition for physical systems. Based on the frequency-domain master curves, the continuous relaxation spectra were calculated and then the storage and loss moduli were approximated by the frequency-domain Prony series. The time domain master curves of the relaxation modulus were obtained by taking the inverse Fourier transform, and the Prony series with fewer terms can be fitted using the time-domain master curves for specific problems.

9058-28

Bayesian techniques to quantify parameter and model uncertainty in smart material systems

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Piezoelectric, magnetic and shape memory alloy (SMA) materials offer unique capabilities for energy harvesting and reduced energy requirements in aerospace, aeronautic, automotive, industrial and biomedical applications. However, all of these materials exhibit creep, rate-dependent hysteresis, and constitutive nonlinearities that must be incorporated in models and model-based control designs to achieve their full potential. Furthermore, models and control designs must be constructed in a manner that incorporates parameter and model uncertainties and permits predictions with quantified uncertainties. In this presentation, we will discuss Bayesian techniques to quantify parameter and model uncertainty in smart material models.

9058-29

Investigation of temperature influence on mechanical properties of graphene oxide thin films

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Graphene, the two dimensional material of graphite family, has drawn extensive attention in the scientific community with its extraordinary mechanical, electrical, and thermal properties. Free-standing paper like materials or foils can be used as protective layers, adhesive layers, components of super-capacitors or batteries, chemical filters, electronic or optoelectronic properties and molecular storage. Previously, flexible graphite foils synthesized from expanded graphite particles had been used in packing and gasketing applications due to chemical stability, thermal resistance, and impermeability to fluids. Inorganic mica platelets have also been studied and commercialized as dielectric barriers, protective coatings, high temperature binders and gas impermeable membranes. Recently, freestanding graphene oxide paper has been synthesized by flow-directed assembly of individual graphene sheets with superior stiffness and strength properties to its predecessors. However, mechanical properties such as Young's modulus and hardness of graphene oxide paper as a function of temperature has not yet been studied. Therefore, in this paper, the temperature influence on the mechanical property of graphene oxide thin films will be investigated. Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD) and Atomic Force Microscopy (AFM), Nano-indentation Machine was used for materials and mechanical properties characterization. Results have shown that the Young's modulus and hardness of graphene oxide paper increased with the increase of temperature at certain range without oxidization.

9058-30

Omniphobic behavior of transparent graphene oxide by trichlorosilane self-assembled monolayers

Dae Hwan Kim, Northfield Mount Hermon (United States)

The control of liquid-repellent surfaces is an essential step in the effort to provide surface functionalization on cars, airplanes, buildings, and medical tubes. Graphene oxide thin film is of particular interest among multifunctional omniphobic devices because of its controllable conductivity, optical transparency, mechanical flexibility, as well as its low-temperature solution process. In this study, the contact angles and slippery properties of graphene oxide and trichlorosilane self-assembled graphene oxide with four different coating thicknesses (60, 120, 240, and 550 nm) were investigated by applying deionized water and three representative types of intravenous solutions (dextrose, normal saline, and Trifusin injection). The contact angles of trichlorosilane self-assembled graphene oxide (92-101°) were approximately 2.5-5.1 times higher than those of graphene oxide (20-38°). The contact angles also remained constant regardless of the thickness of graphene oxide. This is because the wettability of graphene oxide is determined by the surface tension, not the thickness of the graphene oxide. In addition, whereas the intravenous solution droplets remained on the surface of graphene oxide, they trickled down on the surface of trichlorosilane self-assembled graphene oxide without leaving any traces. It is envisioned that omniphobic properties of trichlorosilane self-assembled graphene oxide including its transparency, flexibility, and spray-coatability could be used for various surface types of biotechnological and medical equipment.

9058-31

Physical and mechanical properties of short glass fiber/polyurea composites

Jing Qiao, Chong Wu, Gaohui Wu, Harbin Institute of Technology (China)

The main objective of this study was to evaluate the physical and mechanical properties of glass fiber/polyurea composites. Short E-glass fiber was selected due to its excellent mechanical properties and low cost. Specimens with glass fiber content of 5, 10 and 15 vol% with fiber length of either 154, 104, or 54μm were prepared. Physical properties of the specimens were then tested by fourier transform infrared spectroscopy and thermoGravimetric analyzer. Dynamic mechanical

analysis was conducted using a TA Instruments DMA Q800 over the temperature range from -80°C to 100°C at 1MHz. Compression tests were performed on instron universal materials testing machine and Hopkinson bar apparatus. Six different strain rates were used: 0.001, 0.01, 0.1, 1, 2000 and 3000s-1. We present the results of a collection of experiments for which the fiber length and volume fraction were varied and evaluate the effect of these variables on the properties of the composites.

9058-32

Quantitative analysis on the compressive behavior of vertically aigned carbon nanotubes

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Although there are a number of reports on the compressive properties of vertically aligned carbon nanotubes (VACNTs), no study has been reported on a quantitative analysis on the unique compressive behaviors of VACNTs. In addition, no detailed studies were reported on the anisotropic properties of VACNT arrays. In this paper, millimeter long VACNTs were fabricated by a CVD method and their compressive stress-strain behaviors were characterized and analyzed by considering local buckling of VACNTs. Furthermore, the stress-strain behaviors in compression were quantitatively analyzed by employing a strain energy density function, which can allow us to obtain and compare the material constants including shear modulus, Lamé constant and bulk modulus. Using the strain energy density function, the anisotropic properties of VACNTs in compressions were investigated and quantitatively characterized.

9058-33

Theoretical and experimental studies of small diameter cylindrical IPMC actuators

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This paper presents the electromechanical effects on ionic polymer-metal composite (IPMC) rods through theoretical and experimental work. Firstly, a computational model is created in COMSOL to simulate the bending motion that an IPMC rod undergoes when a voltage is applied. A parametric study is conducted to simulate the different displacements with different applied voltages. Secondly, the COMSOL model and theoretical model is validated through experimental results. IPMC rods are manufactured out of Nafion through the injection molding process, and the electrodes are applied to the Nafion rods. The rods are tested by applying various voltages to them, and the resulting displacements are measured. The results of this study will further the understanding of cylindrical IPMC rods and how they react to different applied voltages. This paper also present results on how mold quality reflects performance of the resulting rod-shaped IPMC.

9058-34

Real-time programmable variable stiffness 2D surface design

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It is well known that there are many engineering applications where variable stiffness features can be effectively utilized from advanced manipulation of articulated robotic arms to impact mitigation. Also, variable stiffness feature can be effectively utilized for the tactile sensory devices in tele-manipulation applications which allows a user to remotely manipulate the object with dexterity and sensing that human use. The proposed 2D design of the variable stiffness surface can be a key component of advanced tactile devices satisfying ever increasing demand for smaller, high resolution, high band-width tactile sensors. Another important engineering application of the proposed variable stiffness device is for shock and vibration isolation due to its high dynamic bandwidth feature. The proposed 2D surface design is based on the Biased Magnetorheological Elastomer (B-MRE). When a magnetic field is applied to the conventional MRE, the iron particles within the elastomer compound develop a dipole interaction energy, which results in an increase of the base elastomer modulus. The novel feature of the B-MRE is its novel feature of introducing a field induced modulus bias via a permanent magnet, which can be offset with a current input to the electromagnetic control coil. This permanent magnet based bias flux and control coil combination leads to the design of the real-time variable stiffness joint which can change the compliance or modulus of a base elastomer in both directions (softer or harder).

9058-43

Anisotropic elastic properties of glancing-angle deposition (GLAD) thin films at micro-scale evaluated by resonant frequency spectra

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Glancing-angle deposition (GLAD) thin films are nano-engineered to meet the requirements of a variety of applications such as micro filters, sensors, and waveguides due to their unique frequency characteristics which cannot be achieved by conventional solid materials. For the design, it is necessary to understand the elastic properties of GLAD thin films. In this paper, we develop an advanced vibration testing technology at micro-scale. In the testing, specially designed micro-specimens with surface area of tens by tens micro meters are excited by a PZT actuator and the resonance frequency is detected by a laser device at the vertical or lateral direction. The anisotropy elastic modulus of GLAD thin films composed of helical nano-springs is evaluated on the basis of vibration testing. The thin film shows strong characteristic anisotropy that the solid one hardly can attain.

9058-44

A stress-induced phase transition model for semi-crystallize shape memory polymer

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The developments of constitutive models for shape memory polymer (SMP) have been motivated by its increasing applications. During cooling or heating process, the phase transition which is a continuous time-dependent process happens in semi-crystallize SMP and the various individual phases form at different temperature and in different configuration. Then, the transformation between these phases occurred and shape memory effect will emerge. In addition, stress applied on SMP is an important factor for crystal melting during phase transition. In this theory, an ideal phase transition model considering stress or pre-strain is the key to describe the behaviors of shape memory effect. So a normal distributed model was established in this research to characterize the

volume fraction of each phase in SMP during phase transition. Generally, the experiment results are partly backward (in heating process) or forward (in cooling process) compared with the ideal situation considering delay effect during phase transition. So, a correction on the normal distributed model is needed. Furthermore, a linear relationship between stress and phase transition temperature is also taken into account for establishing an accurately normal distributed phase transition model. Compared with the other expressions, this new-type model possesses less parameter and is more accurate. Finally, Dynamic Mechanical Analysis (DMA) tests on epoxy and styrene were conducted, the phase transition temperature and the storage modulus of these SMP were also obtained. For the sake of verifying the rationality and accuracy of new phase transition model, the comparisons with the experiment results were carried out.

9058-45

Vibration analysis of an active twist helicopter blade

Ozge Ozdemir, Istanbul Technical Univ. (Turkey)

The helicopter rotor is subject to a three-dimensional, non-symmetric, and time-dependent flow field. As a result of the interaction of elastic blades and the complex aerodynamic environment, rotorcrafts are burdened by large vibratory loads and high noise levels. This can lead to a reduction in handling quality and passenger comfort, limited public acceptance, and reduced service life of critical parts.

With the introduction of smart materials, new noise and vibration control and performance improvement concepts have been recently pursued. Therefore, in the last two decades, active approaches to control helicopter vibration have considerable attention due to their relative advantages over the traditional passive methods. Active blade twist is aerodynamically cleaner and also has a lesser drag penalty, being a continuous structure. Therefore, helicopter integral blade actuation is one example of mostly preferred efforts using embedded anisotropic piezoelectric actuators. Active twist control of the rotor blades may be used to reject the aerodynamic disturbances affecting the blades.

In this paper, vibration analysis of a smart blade is performed. In the first part, analytical formulation is carried out for the beam model that undergoes coupled flapwise bending, chordwise bending and torsion vibrations. The torsional deformation is obtained using anisotropic piezoelectric actuators embedded in the blade construction. For the examined blade model, both the potential and the kinetic energy expressions are derived step by step using explanatory tables and figures.

The Hamilton's principle is applied to to obtain the governing differential equations of motion and the associated boundary conditions. An efficient analytical technique called the Differential Transform Method (DTM) is used in the solution part to transform the governing differential equations of motion and the boundary conditions into simple analytical expressions. Whenever it is possible, validation is made with the results in open literature. When the related results are not available in open literature, the results taken from the finite element programme, ABAQUS, are used for validation. Effects of several parameters on the natural frequencies and the vibration characteristics are presented in several tables and graphics. Consequently, it is observed that the agreement between the results is very good.

9058-46

One-step fabrication of multifunctional silica microbelt with the novel stacked structure by electrospinning technique

Yongtao Yao, Haibao Lu, Jianjun Li, Jinsong Leng, Harbin Institute of Technology (China)

Recently, one-dimensional structures, i.e. fibres, belts, tubes et al, have attracted more attentions based on their unique properties and the versatile applications. Electrospinning technique was common and effective way to fabricate one-dimensional structures with diameters ranging from a few nanometers to several micrometers. In this study, one-step fabrication of electrospun silica microbelt with novel stacked structure and controllable wettability was made based on a combination of sol-gel chemistry and electrospinning techniques. The application field of the one-dimensional silica in different environmental conditions was controlled by functionalization of the hydroxyl groups and non-polar groups on the backbone. The exploration of the one-dimensional stacked structure mechanism was discussed. Experimental results indicate that the formation of one-dimensional stacked structure is strongly related to the conductive properties of collective substrate.

9058-47

Preparation and properties of polyurethane/ silicone materials for biomimetic gecko setae

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In the biomimetic design of gecko setae, it is necessary to select materials with appropriate adhesive properties and to understand the effects of materials on normal and tangential adhesive forces. To meet the adhesion performance requirements of the biomimetic gecko robot foot, in this study, performance-improved polyurethane/silicone polymer materials were designed and synthesized, and the normal adhesion and tangential adhesion were measured using an adhesive friction comprehensive tester. The results show that normal adhesion increased with an increase in load when the normal load is small; when the normal load exceeds a critical value, the increase in normal adhesion slows and adhesion saturates. Under the condition of an adhesive state, the tangential adhesive force was larger for a smaller negative normal force, and a relatively large tangential adhesive force could be generated with a very small negative normal force. The elastic modulus of the synthetic polyurethane/silicone material varied with varying ratios of components, and it increased with increasing urethane content. Polyurethane/silicone material with about 30% polyurethane provided greater adhesion than other materials with different contents of polyurethane. The results provide a basis for the choice of biomimetic materials of the biomimetic gecko robot foot.

9058-48

High cycles fatigue damage of CFRP plates clamped by bolts for axial coupling joint with off-set angle during rotation

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This study discusses the fatigue damage process of thin CFRP plates clamped by bolts for axial coupling joint, in which flexible deformation is allowed in the direction of off-set angle by the deflection of the CFRP plates while effective stiffness is obtained in rotational direction. Mechanically laminated 4 layers of the CFRP plates were repeatedly deflected during the rotation of axial coupling, when two axes were jointed with 3 (and also 0) degree of off-set angle, in which number of revolution was 1,800 rpm (30Hz of loading frequency). At first, variation of static strains on the surface of CFRP plates was investigated when the joint was rotated. The stiffness reduction ratio was also determined by simple bending test after the fatigue. The remained allowable transmitting torque of the joint was determined on the rotational test machine after 1.0?107 cycles of fatigue. Test results showed that change of strains on the CFRP plates were directly related with the rotation of the joint accompanying with the deflections of the CFRP plates. After rotations of cyclic fatigue, fiber breaking and wear of matrix were observed around

the fixed parts compressed by washers for setting bolts. The stiffness reduction of the CFRP plates was caused by the initiation of cyclic fatigue damages around the fixed parts, when the axial coupling joint was rotated with off-set angle. It was also found that allowable transmitting torque of the joint was related with the specific fatigue damage of the CFRP observed in this study.

9058-49

Microstructure, mechanical, and thermophysical properties of Csf/SiC multilayer composites by tape casting and pressureless sintering

Wenshu Yang, Harbin Institute of Technology (China); Sara Biamino, Elisa Padovano, Matteo Pavese, Paolo Fino, Claudio Badini, Politecnico di Torino (Italy)

Silicon carbide (SiC) is one of the most promising materials for thermal protection system (TPS) of future reusable spacecraft. However, its low fracture toughness remains a major concern for its widely application in severe environment.

In order to overcome this shortcoming, several reinforcements have been introduced into SiC to prepare SiC matrix composite. Short C fibre reinforced SiC composites (Csf/SiC) are also wide studied recently shice they could be fabricated by conventional manufacturing techniques which reduce the fabrication cost. Meanwhile, processing ceramics with a multilayer structure is another effective method to improve the toughness of ceramic materials. Multilayer SiC with self-passivating behavior has been proposed as an oxidation-resistant components of TPS. Theoretically, coupling the above methods (multilayer with toughened single composite layer) may further improve the toughness. In the present work, silicon carbide multilayer composites containing short carbon fibres (Csf/SiC) were prepared by tape casting and pressureless sintering. The short C fibres were firstly dispersed in solvents with the aid of dispersant and then mixed with SiC slurry to limit fibre breakage. The average fibre length after mixing was about 0.5 to 0.6 mm, indicating that mixing the SiC slurry with the fibre-predispersed solution is an effective method for adding fibres with limited breakage. The effect of fibre addition on microstructure, mechanical and thermo-physical properties was discussed.

9058-50

Study on microstructure and thermo-physical properties of high volume fraction SiCp/Al composites

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SiCp / Al composites have been widely used in the field of electronic packaging for their excellent properties such as low density, outstanding thermal physical characteristics, etc. Three SiCp/6063 composites, with 55%~ 65% volume fractions, were fabricated by squeeze technology. The microstructure of composites appeared to be homogeneous and SiC particles distributed uniformly in the matrix. The thermal expansion coefficient of composites was about 200~220 W/m•K, increased as SiC content increased. The mean linear CTE(20?~50?) of SiCp/6063 composites, which lied between 10~13?10-6/?, decreased as SiC content increased. This satisfied the requirements in electronic packaging industry.

9058-51

Preparation and damping properties of cenosphere fly ash-aluminum composite

Qiang Zhang, Linchi Zou, Qinlin Guo, Yingfei Lin, Gaohui Wu, Harbin Institute of Technology (China)

The pressure infiltration technique is capable of fabricating lightweight metal matrix foam composites containing hollow particles. Cenosphere fly ash particle, a byproduct of coal combustion wastes, is hollow-structured and has been considered as good filler for foam composites. In this work, an aluminum matrix foam composite was produced by the pressure-infiltrating the commercially pure aluminum into the packed preform of cenosphere fly ash particles. Microscopic observation was done to study the distribution and infiltration status of fly ash particles. The damping properties were evaluated using dynamic mechanical analyzer (DMA). The effects of the strain amplitude, measuring temperature and frequency were discussed. These experiments help to design new foam composites with desirable microstructure and damping properties.

9058-52

Effect of deformation on the friction and wear properties of TiB2/2024Al composite in unlubricated sliding condition

Haitao Chi, Longtao Jiang, Pengchao Kang, Guoqin Chen, Wenshu Yang, Gaohui Wu, Harbin Institute Of Technology (China)

TiB2 /2024Al composites with volume fractions of 30% was designed and fabricated by pressure infiltration technology. By using scanning electron microscope (SEM), friction and wear tester, the friction and wear properties of the TiB2/2024Al composites were studied. The results show that after thermal deformation TiB2 particles were uniformly distributed better and relative density was improved. Study of the friction and wear property showed that the thermal deformation composite had a lower friction coefficient and wear rate, the thermal deformation improved friction and wear properties significantly. SEM morphology of wear results showed that after deformation wear mechanism changed from adhesive wear to abrasive wear.

9058-53

Influence of quenching on expansion coefficient and micro-yield strength of Invar36

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Invar36 is widely used in high-precision instruments because of its low expansion and high dimensional stability. This paper studies the influence of quenching treatment on expansion coefficient, micro-yield strength and microstructure of Invar36. The results showed that with the increase of quenching temperature the expansion coefficient of invar first decrease and then increase. The expansion coefficient of original invar36 will be reduced to the minimum after quenching at 820?, the average coefficient of expansion (as opposed to 20?) ??is about 0.6?10-6, about decreased by 50%. The micro-yield strength also will be increased by 30% to about 125MPa.

9058-54

Modeling and simulation of shape memory behavior and temperature memory effect in polymer undergoing relaxation transition

Haibao Lu, Harbin Institute of Technology (China)

It has been demonstrated that the temperature memorization is induced at the temperature of their initial deformation, a phenomenon known as the temperature memory effect (TME) in shape memory polymer (SMP). In this study, the working mechanism and theoretical feature behind the TME and shape memory effect (SME) are identified, as expected from the relaxation law. A thermodynamic constitutive framework for the shape recovery behavior and temperature memorization in SMPs is proposed based on the relaxation law and Tool-Narayanaswamy (TN) equation, respectively, and incorporating them with parameters (relaxation time, saturated water vapor pressure, output cargo and transition temperature) as functions of frequency. Finally, the simulation of the phenomenological model is compared with the available experimental results in the literature for further verification.

9058-55

Multi functional devices combines shape-memory alloy to piezo electric material

Hiroshi Sato, National Institute of Advanced Industrial Science and Technology (Japan)

The shape-memory alloy, for example NiTi, uses actuator by the shape memory effect and the effect of super-elasticity. And piezoelectric material, for example PZT, uses actuator and sensor by piezoelectric effect and pyroelectric effect. However, each of the materials has been used for the sensor and the actuator independently because the principle of the function of each of materials is different. In this research, a new multifunctional device that united these four functions was developed by coating the PZT thin film to the surface of the NiTi wire by hydrothermal method.

The shape memory array wire coated PZT thin films has four effects; a shape-memory effect; superelasticity effect piezoelectric effect; and pyroelectric effect. Those effects can perform the mutual transformation among mechanical energy, thermal energy and electric energy. In the multifunctional device, each of the effects generates not independently.

In the future, it will be develop the multi functional device which including the remaining two effects (shape memory effect and pyroelectric effect). By fusing these functions, we will produce new sensor actuator system such as the self-sensing actuator where transformation by shape memory effect is detected by piezoelectric effect or pyro-electric effect, or rough and precision actuator that does rough movement by shape memory effect and does precise movement by piezoelectric effect.

9058-56

Preliminary design and analysis of a cubic deployable support structure based on shape-memory polymer composites

Fengfeng Li, Liwu Liu, Yanju Liu, Jinsong Leng, Harbin Institute of Technology (China)

Lunar expandable habitat is a critical component of the future lunar exploration, and the deployable support structure is perhaps the most complex element in the habitat. Considering the structural fundamental and the capability of active shape-changing of shape-memory polymer composites (SMPC), we preliminarily designed and analysed a cubic deployable support structure based on shape-memory polymer composites of lunar expandable habitat. First of all, we selected a type of epoxy SMP which is better for using in aerospace. It showed high glass transition temperature Tg, excellent mechanical properties, large reversible deformation, good anti-radiation performance. Secondly, by introducing the theoretical equations of laminated composites and theoretical mechanics of material we simulated and designed a type of arc-shaped deformable laminate then evaluated the shape recovery time of bending laminate; compared actual laminate reply force with the output torque of bending laminate in finite element simulation. Thirdly, the cubic deployable support structure based on SMPC was designed and optimized. It is composed of twelve beams, the beams are designed to create a cubic cage. Each beam is made up of spindle sleeves, arc-shaped deformable laminates and connectors. The shape recovery of laminates drive spindle sleeves to unfold, thus realize the expansion of the deployable support structure. Finally, we fabricated the model cubic deployable support structure and carried out tests on the ground, compared the actual process of structure unfolding with process of structure unfolding in dynamics simulation; compared the structure' modal parameters by using experimental modal analysis with the one by using ABAQUS software. The cubic deployable support structure performs long duration exploration, high packaging efficiency for launch, reduced mass, self-deployment, improved robustness for lunar expandable habitat and mechanically simple components.

9058-57

A multiscale-based model for composite materials with embedded PZT filaments for energy harvesting

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This current study focuses on utilizing Composite Materials with Embedded PZT Filaments for Energy Harvesting. It represents a multi-scale approach to model embedded PZT filaments in polymer based composite material. The work presented models multifunctional composite materials and structures on multiscales considering piezoelectric response to mechanical loads for the reinforcement of unidirectional composites, which are used to construct laminates of a general layup; both membrane and bending vibrational loads are considered.

The solution for the local fields is determined in terms of a transformation field analysis scheme in which the local stresses or strains, which are cannot be removed by mechanical unloading are treated as eigen fields applied in an otherwise elastic medium. In the current application, the latter represents an aggregate of unidirectional plies and their phases. Both two phase models such as the Mori-Tanaka model and periodic array models are employed. The solution for the overall response is determined in terms of refined plates theory using Carrera unified formulation. The overall electro-mechanical properties used are obtained from the transformation field analysis conducted earlier.

The proposed modeling strategy is applied to fibrous laminates subjected to mechanical loads. These results were then verified experimentally by using piezoelectric ceramic composites. These smart structures will be an important component in future designs of energy harvesting and multi-functional devoices to increase efficiency and recover energy.

9058-35

Thermodynamics and nonlinear mechanics of materials with photoresponsive microstructure *(Invited Paper)*

William S. Oates, Jonghoon Bin, The Florida State Univ. (United States)

The ability to directly convert visible light radiation into useful mechanical

work provides many opportunities in the field of smart materials and adaptive structures ranging from biomedical applications to control of heliostat mirrors for solar harvesting. The complexities associated with coupling time-dependent Maxwell's equations with linear momentum is discussed by introducing a set of electronic order parameters that govern the coupling between electromagnetic radiation and mechanics of a deformable solid. Numerical examples are given illustrating how this methodology is applied to a special class of liquid crystal polymer networks containing azobenzene. The dynamics associated with light absorption and its effect on deformation of the polymer are solved in three dimensions using finite difference methods and compared with experimental results. Particular emphasis is given illustrating the effect of polarized light on microstructure evolution and stresses associated with dynamic behavior of the internal material state induced by the electromagnetic light waves.

9058-36

Photoactive and self-sensing P3HT-based thin films for strain and corrosion monitoring

Kenneth J. Loh, Donghyeon Ryu, Univ. of California, Davis (United States)

The main goal of this study was to develop a self-sensing nanocomposite for monitoring strain and corrosion (i.e., pH) occurring in various aerospace structures. In particular, the design requirement considered the fact that certain aerospace structures (e.g., reusable spacecraft) could not access a continuous power source and, at the same time, could not support large, bulky instrumentation. Thus, previous studies demonstrated that poly(3-hexylthiophene) (P3HT)-based thin films could be engineered to achieve self-sensing. First, self-sensing was derived from the fact that the film does not depend on an external power source for operations, but instead, electrical current (i.e., photocurrent) could be generated when the sensor was interrogated using a light source. Second, being a thin film, the flexible sensor could be coated onto various types of structural surfaces without drastically affecting its host structure's performance and payload capacity. In this study, the photoactive thin film was encoded with multi-modal sensing capabilities, and in particular, to monitor strain and pH (which is an indicator of corrosion). The sensitivity to strain and pH was characterized through extensive laboratory testing by subjecting the films to different loading scenarios and different pH buffer solutions, respectively. Their selectivity to each damage mode was also investigated so that the proposed films could differentiate the type of damage occurring in the structure.

9058-37

Thermal response of novel shape memory polymer: shape memory alloy hybrids

Jonathan M. Rossiter, Univ. of Bristol (United Kingdom); Toshiharu Mukai, RIKEN (Japan); Kazuto Takashima, Kyushu Institute of Technology (Japan)

Shape memory polymers (SMP) and shape memory alloys (SMA) have both been proven important smart materials in their own fields. Shape memory polymers can be formed into complex three-dimensional structures and can undergo shape programming and large strain recovery. These are especially important for deployable structures including those for space applications and micro-structures such as stents. Shape memory alloys on the other hand are readily exploitable in a range of applications where simple, silent, light-weight and low-cost repeatable actuation is required. These include servos, valves and mobile robotic artificial muscles. Despite their differences, one important commonality between SMPs and SMAs is that they are both typically activated by thermal energy. Given this common characteristic it is important to consider how these two will behave when in close environmental proximity, and hence exposed to the same thermal stimulus, and when they are incorporated into a hybrid SMA-SMP structure. In this paper we propose and examine the operation of SMA-SMP hybrids. The relationship between the two temperatures Tg, the glass transition temperature of the polymer, and Ta, the nominal austenite to martensite transition temperature of the alloy is considered. We examine how the choice of these two temperatures affects the thermal response of the hybrid. Electrical stimulation of the SMA is also investigated as a method not only of actuating the SMA but also of inducing heating in the surrounding polymer, with consequent effects on actuator behaviour. Likewise by varying the rate and degree of electrical stimulation of the SMA significantly different actuation and structural stiffness can be achieved. Novel SMP-SMA hybrid actuators and structures have many ready applications in deployable structures, robotics and tuneable engineering systems.

9058-38

Internal loops in torsional response of superelastic SMA wires: an experimental investigation

Arun R. Srinivasa, Ashwin Rao, Annie Ruimi, Texas A&M Univ. (United States)

The goal of this work is to understand the torsional response of superelastic SMA wires under different extent of loading and unloading levels that can result in partially and fully transformed cases.

Currently available experiments on Torsion of sma wires are restricted to the small strain regime (involving only a limited extent of transformation). The current study involves the twisting of a superelastic SMA wire so that transformation is nearly complete. Futhermore, we study the effect of unloading after different partial transformations (both during the loading phase and the unloading phase as well as reloading after partial unloading) to document the return point memory (RPM) phenomenon.

From an application standpoint, improved understanding of torsional responses under partial or fully transformed cases with internal loops is of particular importance as in many cases not the entire response is utilized and only a partial internal loop might be of significance. Various experimental cases and model simulations/predictions discussed in this work will help designers analyse SMA components under different extents of twisting levels and transformation extents.

9058-39

A rate-dependent tension-torsion constitutive model for superelastic Nitinol under non-proportional

Rasool Rahmanian, The Univ. of Toledo (United States)

A non-Mises based 3-D model is presented to capture the multiaxial behavior of superelastic shape memory alloys (SMAs) under quasi-static isothermal and dynamic anisothermal loading states. General experimental based equivalent stress/strain terms are introduced and corresponding flow rule and transformation surfaces are presented. The constitutive equations are found and discussed in details for both isothermal and dynamic loading conditions. An extended experimental study is conducted on NiTi thin walled tubes to investigate the functionality of the model. The model is also implemented into a finite element platform via a UMAT subroutine to simulate complicated thermo-mechanical loading histories. The approach is shown to be able to capture the SMA response better than the original model in combined tension-torsion loading conditions.

9058-40

A three-species model for simulating torsional response of shape memory alloys

Arun R. Srinivasa, Ashwin Rao, Texas A&M Univ. (United States)

In this work, athree species model is proposed to capture the complete torsional response of SMA components. By extendingRao and Srinivasa's approach (IJSS, 2013), a Gibbs potential based formulation that combines both thermaland mechanical loading is developed. The model is formulated directly in terms of experimentally measurable quantities torque–angle of twist rather than solving for these using non-homogeneous shear stress across the specimen. The core idea is in separating the thermoelastic and dissipative parts of the response and capturing the dissipative part of the response using a discrete Preisach model. The approach is can simulate bothsuperelastic and shape memory response under clockwise and anticlockwise torsional loading cases. The model results are verified with the available experimental data for predicting responses at different twists and operating temperatures.

9058-41

Load bearing and stiffness tailored nitinol implants produced by additive manufacturing

Mohammad H. Elahinia, Christoph Haberland, The Univ. of Toledo (United States)

Common metals for stable long-term implants (e.g. stainless steel, Titanium and Titanium alloys) are much stiffer than spongy and even stiffer than cortical bone. When bone and implant are loaded this stiffness mismatch results in stress shielding and as a consequence, degradation of surrounding bony structure can lead to disassociation of the implant. Due to its lower stiffness and high reversible deformability which is associated with the superelastic behavior, Nitinol is an attractive biomechanical material for load bearing implants. However, the stiffness of austenitic Nitinol is closer to that of bone but still too high. Additive manufacturing provides in addition to the fabrication of patient specific implants also the ability to solve the stiffness mismatch by adding engineered porosity to the implant. This even allows for the design of different stiffness profiles in one implant tailored to the physiological load conditions. This work covers a fundamental approach to bring this vision to reality. At first modeling of the mechanical behavior of different scaffold designs are presented that proof the concept of stiffness tailoring. Based on these results different Nitinol scaffolds are produced by additive manufacturing. The mechanical behavior of these scaffolds is carried out by compression testing series. Comparisons to the modeling results show that there is a good correlation but more important this work this work clearly demonstrates that additive manufacturing provides an attractive method to produce Nitinol implants and to tailor their stiffness profiles according to physiological load conditions.

9058-42

Three dimensional magnetomechanical response of a NiMnGa magnetic shape memory alloy

Constantin Ciocanel, Heidi P. Feigenbaum, Isaac D. Nelson, Douglas H. LaMaster, Northern Arizona Univ. (United States)

Magnetic shape memory alloys, such as NiMnGa, are commonly used for practical applications involving either actuation, sensing, or power harvesting. The magnetomechanical response of the material under loading conditions specific to these applications has been extensively investigated. However, this data is not comprehensive enough to be used for calibration and validation of a three dimensional constitutive model developed for these materials. Accordingly, this paper presents experimental data that was acquired by loading the material in all three orthogonal directions, in a variety of loading configurations. The acquired data is then compared to predictions made using a general constitutive model under development by the authors.

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9059-18

Optimal design of a novel configuration of MR brake with coils placed on side housings

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It is well known that, in design of traditional magneto-rheological brake (MRB), coils are placed on the cylindrical housing of the brake. In this study, a new configuration of MR brake with coils placed on the side housings of the brake is proposed and study. After an introduction of the proposed configuration, braking torque of the MR brake is analyze based on Bingham-plastic rheological model of MR fluid. The optimization of the proposed and conventional MR brakes is then performed considering maximum braking torque and mass of the brake. Based on the optimal results, a comparison of the proposed MR brakes and the conventional ones is undertaken. In addition, experimental test of the MR brakes is conducted and the results are presented in order to validate the performance characteristics of the proposed MR brake.

9059-20

Multilevel optimization for the placement of Piezo actuators on plate structures for active vibration control using modified heuristic genetic algorithm

Deepak Chhabra, Maharshi Dayanand Univ., Rohtak (India); Gian Bhushan, Pankaj Chandna, National Institute of Technology, Kurukshetra (India)

The present work deals with the optimal placement of piezoelectric actuators on a thin plate via modified control matrix and singular value decomposition (MCSVD) approach using Modified Heuristic Genetic Algorithm (MHGA). The cantilever isotropic square plate with piezo-patches has been formulated with 8x8 quadrangular elements; each element with 4 nodes and each node is having 3 degree of freedom. The effects of piezoelectric mass, stiffness and electromechanical coupling have been taken in to account while modeling the structure in state space form. In the present case, optimal placement of piezoelectric actuators is investigated to suppress the first six modes. Vibration suppression has been studied for cantilever plate with piezoelectric patches in optimal positions using LQR (Linear Quadratic regulator) scheme. Further, the closed loop average damping ratio has been considered as a fitness function to determine the weighing matrices of LQR controller while keeping actuators voltages within the limit of breakdown voltage and maximizing it with Genetic Algorithm (GA). It is observed that developed MCSVD approach using MHGA has given the greater closed loop average damping ratio and lesser computational requirements. Moreover, developed GA-LQR has resulted in greater vibration reduction and drastic increase in maximum control voltage.

9059-21

Study on sliding joint of curtain wall support structure of Shanghai Tower

Li Jiupeng, Tongji Univ. (China)

126-story?632-meter tall shanghai tower?is sited in Shanghai's Lujiazui Finance and Trade Zone, structure height of which is 580m. It will be the Landmark of shanghai, after completing construction. The tower has a unique design with an inner and outer "double-skin" curtain wall system.

Shanghai tower is divided in nine zones by refuge floor and mechanical floor. In each zone the outer exterior wall twists and tapers around the inner cylindrical building , extending vertically vary from 12 stories to 15 stories in height.

Because of the exterior curtain walls with the unique architectural style and far away from the main structure suspended in ultra-high-rise buildings, An unique and flexible hanging curtain wall support structure (CWSS) was developed to suit the external curtain wall system of Shanghai Tower.

Because the huge height of CWSS,The relative vertical displacement between the main structure and CWSS occured in the construction and service stage is large.In order to ensure the curtain wall system safe, a large number of the connections which can absorb relative deformation are set up between the curtain wall and main structure to avoid exaggerated vertical displacement, which generates excessively additional internal force to make the curtain wall structure failure.

In order to ensure the service of curtain wall systems, the new sliding joint was adopted to release the relative displacement between the curtain wall system and the main structure, which can avoid the additional internal force of CWSS. Under the complex stress state, sliding joints may be self-locking, which makes the curtain wall fail. In this paper, the sliding performance of sliding joint of CWSS and the strength of joints are analyzed and studied, which is based on the finite element analysis and experiment test. Studies show that self-locking won't happen and the structure of sliding joint meets the design requirements.

9059-23

Special optical fiber design to reduce reflection peak distortion of a FBG embedded in inhomogeneous material

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During the last decades, the use of optical fiber for sensing applications has gained increasing acceptance because of its unique properties of being intrinsically safe, unsusceptible to EMI, potentially lightweight and having a large operational temperature range. Among the different Fiber Optic sensor types, Fiber Bragg Grating (FBG) is most widely used for its unique multiplexing potential and the possibility of embedding in composite material for Structural Health Monitoring. When the fiber is embedded in an inhomogeneous environment, typically a material composed of a filler and base material of different stiffness, local stiff material will generate extra lateral load to the fiber. Via the Poisson effect, this will be converted to a local axial strain. The narrow and sharp peak in the reflection spectrum of an FBG sensor relies on the constant periodicity of the grating. An inhomogeneous axial strain distribution will result in a distortion or broadening of the FBG reflection spectrum. For the FBG strain sensitivity of about 1pm/??, the spectral distortion can be disastrous for strain measurements. A fiber design to tackle this critical problem is presented. Finite Element Modeling is performed to demonstrate the effectiveness of the solution. Modeling with different configurations has been performed to verify the influence of the design. The deformation of the core in the special fiber depends on the design. For a particular configuration, the core deformation in the axial direction

is calculated to be a factor of 10 lower than that of a standard fiber. The first prototype fiber samples were drawn and the manufacturing of FBG in this special fiber using the phase mask method was demonstrated successfully.

9059-24

A progression of damage repair capability in selfrepairing composites

Carolyn M. Dry, Natural Process Design, Inc. (United States)

This paper covers several projects in which the author sought to determine the extent of damage against which self repair would be effective. So far no limits have been reached beyond those of the fiber/matrix itself.

Starting with barely visible damage NPD repaired airplane wings consisting of graphite fiber/resin matrix composites; Next ballistic damage of vinyl ester walls and epoxy resin walls were repaired; Next blast damage repair of walls was assessed; Finally blast and ballistic damage were combined. This paper covers all of these damage scenarios up to and including ballistic damage which is incendiary.

This paper covers data and test results showing this progression.

9059-25

Comparison of self repair in various composite matrix materials

Carolyn M. Dry, Natural Process Design, Inc. (United States)

In a comparison of self repair in graphite composites (for airplane applications) versus epoxy and vinyl ester composites (for building structures or walls) 1 the type of damage that the fiber/matrix is prone to experience is a prime factor in determining which materials self repair well and 2 the flow of energy during damage determines what kinds of damage they can repair.

1) In brittle composites repair was successful throughout the composite due to matrix cracking which allowed for optimum chemical flow, whereas in toughened composites that did not crack, the repair chemical flows into a few layers of the composite.

2) If the damage energy is stopped by the composite and goes laterally, it causes delamination which will be repaired; however if the damage energy goes through the composite as with a puncture, then there will be limited delamination, less chemical release and less repair.

This paper covers data and test results showing these differences.

9059-26

Sensing of repair in chemically self-repairing composites

Carolyn M. Dry, Natural Process Design, Inc. (United States)

The question to be answered in this paper is how “does a user determine if a chemical self repair system has succeeded in self repairing damage”. Three sensing methods indicated that chemical has been released into damage areas, another four methods were used to indicate that the container or encapsulator had been broken to release repair chemical, but only one method is known to indicate that the chemical reaction of the repair chemical has been accomplished. Many other methods were used to assess the structural or dynamic efficacy of the repairs. These methods of sensing of repair action are detailed with experimental data and results. The novel and ground breaking method of determining repair efficacy receives most emphasis.

9059-27

Thixotropic action of self-repairing chemicals to increase strength at first impact

Carolyn M. Dry, Natural Process Design, Inc. (United States)

Thixotropic aspects of self repairing chemicals increase strength at first impact in addition to self repairing strength in subsequent impact damage The samples with thixotropic repair chemical were compared to samples with repair chemical that is not thixotropic. The flow rate and initial impact resistance were assessed. In theory, thixotropic chemicals are thicker and stiffer upon impact, until impacted at which time they flow more effectively than non thixotropic chemicals. Samples with thixotropic additives may make the ballistic panels tougher and more shear and fatigue resistant.

The idea was to make repair chemical thixotropic to:

i) Increase strength upon initial impact.

ii) Better and evenly distribute the repair chemical throughout the delamination

iii) Assist in energy absorption of subsequent impacts.

Thixotropic liquid or gel becomes thinner with shear. The thixotropic additive was tested through mixing with repair chemical and then tested in CAI testing and ballistic impacts.

9059-1

Synthetic jet actuators for aerodynamic flow control *(Invited Paper)*

Ari Glezer, Georgia Institute of Technology (United States)

The formation and evolution of a synthetic (zero net mass flux) jets and their applications to aerodynamic flow control will be discussed. An isolated synthetic jet is produced by alternating momentary ejection and suction of fluid across an orifice such that the net mass flux is zero. A unique feature of these jets is that they are formed entirely from the working fluid of the flow system in which they are deployed and thus can transfer linear momentum to the flow system without net mass injection across the flow boundary. Extensive experimental and numerical investigations of plane and round synthetic jets have emphasized a compact flow actuator in which the orifice forms one of the surfaces of an otherwise sealed shallow cavity where the flow is driven by the motion of one or more diaphragms (or pistons) that are built into one of the cavity walls. These jets can be produced over a broad range of length and time-scale and their unique attributes make them attractive fluidic actuators for a broad range of flow control applications. The interaction of synthetic jets with an external cross flow over the surface in which they are mounted can displace the local streamlines and induce an apparent or virtual change in the shape of the surface and thereby effect global flow changes and consequently in aerodynamic forces on length scales that are one to two orders of magnitude larger than the characteristic scale of the jets.

9059-2

Development and test of synthetic jet actuators based on dual transducer concept

Martin Schueller, Mathias Lipowski, Fraunhofer-Institut für Elektronische Nanosysteme (Germany); Robert Schulze, Technische Univ. Chemnitz (Germany); Perez Wiegel, Thomas Otto, Thomas Gessner, Fraunhofer-Institut für Elektronische Nanosysteme (Germany)

Synthetic Jet Actuators (SJA) are micro fluidic devices with low power and high compactness. They are used for different applications that require a directed air flow. These kind of fluidic generators require zero mass input and produces non-zero momentum output. The classic design of such an actuator consists of a membrane located on one wall of a small cavity and an orifice that is typically on the opposite of the membrane. In the new SJA concept a Helmholtz resonator is equipped with two transducers to increase the performance of the actuator. The piezoelectric membranes generate the volumetric flow symmetrically from both sides of the chamber. A common outlet connects them to the acoustic far field. A network model was used for designing and optimizing the SJA. Based on this, a double-wall actuator (DWSJA) was developed. In this paper a new design of SJ actuators is presented that was developed to enhance the performance and to increase the velocity of the generated air flow. The new design is based on two membranes, which are oscillating synchronously. The simulation results show that using two transducers does not fully double the exit velocity, but it still shows major improvement over conventional SJA with single transducers. The simulations have been verified by measuring the exit velocity using hot-wire anemometry. The major improvement over SJAs with single transducers is the increased exit velocity by whereas the volume consumption is the same for both concepts.

9059-3

Displacement amplified synthetic jets

Steven F. Griffin, Shawn Haar, Boeing LTS Inc. (United States); Edward A. Whalen, The Boeing Co. (United States)

Synthetic jet actuators are attractive devices for active flow control because, in contrast to many other actuators, they do not require a pressurized air source. Instead, they cyclically ingest and expel air from the external flow that is being controlled. To accomplish this, a piston or diaphragm of some sort is used compress and expand the volume of the actuator cavity. Various approaches to compress and expand the volume of the cavity have been explored including: speaker drivers, mechanical pistons and piezoelectric diaphragms.

Piezoelectric-diaphragm synthetic jet actuators have, in recent years, become the style of synthetic jet actuators most commonly used in active flow control applications. This is largely due to the fact that they only require electrical input, are relatively compact, can operate over a broad range of frequencies and provide the necessary control authority for wind tunnel applications. However, as active flow control applications have increased in scale toward flight, it has become apparent that the control authority of synthetic jets is not sufficient. There has been much work done to increase the control authority of diaphragm based piezoelectric synthetic jets in recent years. However, a more significant leap in performance is required for flight-scale applications such as separation control.

Modeling of synthetic jet actuators is a challenging problem due to the unsteady nature of the device as well as the electro-mechanical coupling and the fluidic-mechanical coupling inherent in the device. If synthetic jet actuators are to be designed and implemented at an industrial scale though, modeling will be required to design them without extensive parametric study in the lab, as is done now. Lumped element modeling is one of the only approaches that considers the complete system, from the electrical input to the fluidic output, and has demonstrated its ability to predict jet velocity and pressure as a function of input frequency and voltage. Analytical models have been developed that focus mainly on the fluidic or fluidic-mechanical components of the actuator and have demonstrated their ability to simulate synthetic jet actuator performance. Focusing entirely on the fluidic portion of the actuator, formation criteria for synthetic jets have been described. These formation criteria provide some excellent guidelines for preliminary design and to establish some boundaries of the actuator design space.

The synthetic jet described in this paper is designed to use a mechanical amplification of piezoceramic stacks via a unique flexure design to drive a piston/cavity at a coupled resonance. The piezoceramic stacks apply forces on the flexure, causing the resulting amplified motion of the piston. The uncoupled, in vacuo mechanically amplified piston displays a resonance that moves the piston in a direction normal to the piston surface. The frequency of this resonance depends primarily on the stiffness of the piezoceramic stacks, the mechanical amplification of the flexure and the mass of the piston. For a fixed mass, more mechanical amplification leads to a lower frequency. The cavity displays a resonance that has a velocity maximum (pressure minimum) at the jet aperture and an average high pressure along the piston. This resonance is largely determined by its depth and not its volume or the size of the aperture. In this way it is more like a pipe resonance than a Helmholtz resonance. The goal in modeling this device was to design resonant and mechanical amplification to produce the maximum momentum metric of interest.

The method used to calculate jet velocities and other metrics of interest including acoustic potential energy, total momentum and time average momentum for each design variable configuration was a fully coupled structural acoustic model using the modal interaction method. The method uses in vacuo structural modal analysis results from a structural finite element model of the mechanically amplified piston and blocked wall acoustic modal results from an acoustic finite element model of the cavity. These modal results are combined with calculated coupling matrices to predict transfer functions in the Matlab environment. This approach has displayed good agreement with a fully coupled structural acoustic finite element modeling approach but has the advantage of direct access to coupling terms and easy manipulation of data using control and signal processing tools in Matlab. The input to the assembled transfer function model is the voltage into the piezoceramic stacks. The outputs are the accelerations, velocities and displacements of the piezoceramic stacks and pistons and the pressure inside the cavity.

The transfer function model does not have jet velocity as a direct output. For the purposes of comparison between different configurations, it was assumed that the jet flow could be derived from the acoustic potential energy in the cavity when driven at the maximum piston velocity frequency predicted by the model. Acoustic potential energy defined over the volume, V, of the cavity is

E_p=1/(4?c^2) ∫_V??|p|^2 dV?

where p is pressure inside of the cavity, ? is the density of the air and c is the speed of sound. The discretized version of this integral for use with the modal interaction model is

E_p=1/(4?c^2) “p” ^T “Vp”

where p is a vector of predicted pressures at each node in the cavity and V is a diagonal matrix of the volumes associated with each of the nodes in the volume. This acoustic potential energy was assumed to be converted into kinetic energy with the mass term derived from the dimensions of the aperture. The resulting equation for jet velocity is

v=√((2E_p)/?Al)

where ? is the air density and l is the corrected air mass length. Additionally, a friction drag term was added that contributed to damping in the acoustic mode.

A prediction of jet velocity using this approach for a synthetic jet with a 2.5 mm x 51 mm aperture is shown and is compared to test results. The described coupled structural acoustic model accurately predicted trends with varying aperture size in velocity, total momentum and time averaged momentum and a reasonable job of predicting absolute values of these quantities. Errors in velocity prediction ranged from 3% to 14% while errors in predicted total and time averaged momentums were larger with total momentum showing a maximum error of almost 50% and time averaged momentum showing a maximum error of around 30%. Considering that no tuning of the finite element model was pursued, all of these errors were reasonable. The fact that the model accurately predicted that the highest velocity configuration was not the highest momentum configuration was also encouraging.

9059-4

An Overview of Active Flow Control Actuators and Applications

Daniel Brzozowski, Edward A. Whalen, The Boeing Co. (United States)

Active Flow Control (AFC) is an emerging technology which promises performance enhancements to both military and civilian aircraft. A technique which uses energy input at discrete locations to manipulate the flow over an aerodynamic surface, AFC may be used to reduce drag, prevent flow separation, and enable otherwise-infeasible aerodynamic designs. Additional applications include shear layer and turbulence control for aero-optics applications and mixing enhancement for thermal applications. Many AFC applications call for a high frequency fluidic perturbation provided by an electrically-powered actuator. In these instances, piezoelectric (PZT) materials have served as the workhorse for flow control actuators, such as the widely-studied synthetic jet. Because the PZT materials form the critical component of the actuator, the maximum performance of the synthetic jet (velocity and momentum output) is limited by the physical limitations of the PZT material. The purpose of this presentation is to provide a high level overview of AFC actuators and applications in an attempt to engage the smart materials community and encourage advanced material development in support of these crucial applications.

9059-5

Ultrasonic additive manufacturing of smart structures *(Invited Paper)*

Marcelo J. Dapino, The Ohio State Univ. (United States)

Ultrasonic additive manufacturing (UAM), a form of 3D printing based on ultrasonic metal welding, offers promise for the development of adaptive structures with seamlessly embedded sensors and actuators. UAM combines solid-state ultrasonic welding of metallic foils, automated additive foil layering, and a CNC machining center to create complex and relatively large metallic components fabricated at or near room temperature. A sonotrode driven by a piezoelectric transducer imparts ultrasonic vibrations to a metal foil creating a scrubbing action and plastic deformation between the foil and the material to which it is being welded, often a metallic baseplate, a part, or other foils. Periodic machining or laser etching are utilized in a subtractive fashion to create internal channels for thermal management of final parts or for surface modification of embedded fibers. Recently developed Very High Power UAM delivers 9 kW of ultrasonic energy to the weld interface, which improves the strength and quality of UAM builds, greatly enhances the ability to weld drastically dissimilar materials, and enables previously unfeasible smart structures. This presentation describes current efforts at The Ohio State University in VHP-UAM which are aimed at embedding PVDF, FeGa, and NiTi alloys into metal matrices. Applications to be discussed include thermally invariant composites, stiffness-tunable structures, and built in sensors for structural health monitoring.

9059-6

Interfacial shear strength estimates of NiTi-aluminum matrix composites fabricated via ultrasonic additive manufacturing

Adam J. Hehr, Joshua D. Pritchard, Marcelo J. Dapino, The Ohio State Univ. (United States)

The purpose of this study is to understand and improve the interfacial shear strength (ISS) of metal matrix composites fabricated via very high power (VHP) ultrasonic additive manufacturing (UAM). UAM combines the solid-state ultrasonic welding of metallic foils, an automated foil feeder to build-up material in an additive fashion, and a CNC machining center for periodic machining of components during and post welding. The result is an additive manufacturing process where complex and relatively large metallic components can be fabricated at or near room temperature. VHP-UAM is a key improvement in the original UAM process where the ultrasonic weld power has increased nearly an order of magnitude. This increase in weld power remedies poor interfacial properties observed in early UAM processes. As a consequence of VHP-UAM's low formation temperature, recent efforts have been devoted to the fabrication of aluminum matrix composites with embedded NiTi shape memory alloy fibers for thermal expansion control applications. VHP-UAM NiTi-Al composites have shown a dramatic decrease in thermal expansion in the aluminum matrix, yet thermal blocking stresses developed during thermal cycling have been found to degrade and eventually cause interface failure. As a result, to improve understanding of the interface and guide the development of stronger NiTi-Al composites, ISS was investigated through the use of single fiber characterization methods developed within the fiber composite industry. In addition to estimating ISS, the influence of various fiber surface treatments on interface properties was studied in order to potentially improve ISS. Bond characteristics were studied with the use of various microstructure characterization tools.

9059-7

Stiffness tuning of FeGa structures manufactured by ultrasonic additive manufacturing

Justin J. Scheidler, Marcelo J. Dapino, The Ohio State Univ. (United States)

This paper investigates the manufacture, dynamic modeling, and experimental characterization of metallic structures containing magnetostrictive Galfenol (Fe100-xGax) with respect to semi-active control of the structures' stiffness through bias magnetic field tuning. Galfenol is well suited for vibration control applications due to its frequency bandwidth on the order of 10 kHz, ability to be magnetized easily, and very low hysteresis. Galfenol-Al composite beams are manufactured using ultrasonic additive manufacturing (UAM). UAM is an emerging solid-state welding process that creates metallic bonding between metal foils at peak temperatures below 35% of the foil melting points, which allows for the manufacture of multifunctional composites that contain embedded smart materials. A 1D distributed parameter model of the beams' nonlinear bending vibration is presented. Resonance frequencies are efficiently calculated using autoresonant control. Tunability of the beams' stiffness is quantified by calculating the resonance frequency as a function of mode number, operating conditions, and the composite's cross-sectional geometry. Transverse vibration of the composite beams is measured using a scanning laser vibrometer. The experimental tunability of the beams' first three resonances is characterized from vibration measurements obtained at different bias magnetic fields and excitation power levels. The bending vibration model is used to approximate the corresponding stiffness change for a measured resonance frequency change.

9059-8

Optimal welding parameters for very high power ultrasonic additive manufacturing of smart structures with aluminum 6061 matrix

Paul J. Wolcott, Adam J. Hehr, Marcelo J. Dapino, The Ohio State Univ. (United States)

Ultrasonic additive manufacturing (UAM) is a recent solid state manufacturing process that combines additive joining of thin metal tapes, with subtractive milling operations to generate near net shape metallic parts. Due to the minimal heating during the process, UAM is a proven method of embedding Ni-Ti, Fe-Ga, and PVDF to create active metal matrix composites. Recently, advances in the UAM process utilizing 9 kW very high power (VHP) welding has shown improvements in UAM material properties as well as enabling joining of high strength materials previously unweldable using 1 kW low power UAM. Consequently, a design of experiments study was conducted to characterize and compare VHP UAM aluminum 6061 components against homogeneous material. This understanding is critical in the design of UAM parts containing smart materials. Build parameters, including weld force, weld speed, amplitude, and temperature were varied based on a Taguchi experimental design matrix and tested using two mechanical strength tests. One test is based on ASTM D3165 lap shear testing, which uses tensile loading along a given weld interface to determine shear strength, while the other test developed is a push pin test designed to measure delamination of the UAM build. Based on the mechanical strength test results, optimal weld parameters were identified using statistical methods including a generalized linear model for analysis of variance (ANOVA), mean effects plots, and interaction effects plots. Using these process conditions will lead to optimal mechanical strength characteristics and can be used when designing and implementing active metal matrix composites.

9059-9

Piezoelectric-based electrical energy harvesting and storage methods and electronics for munitions

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The Armament Research development Center (ARDEC) and the Army Research Laboratories in Adelphi, Maryland, and their small business collaborator (Omnitek Partners, LLC) have been developing energy systems that can serve as alternatives to current reserve batteries in certain applications in gun-fired munitions. These energy systems rely on electrical energy that is harvested during the launch and the flight. Harvested energy from the launch and the flight of gun–launched munitions is used to charge a storage device such as a capacitor or an ultra-capacitor. The work to be presented focuses on the coupling of the energy harvester and the appropriate matching of the harvester output parameters with the storage medium in order to achieve optimum efficiency considering the strict requirements of munitions applications. It is shown that using a novel passive method, efficiency of over 70 percent could be achieved in the transfer of the generated electrical charges to appropriately selected storage medium.

The paper also describes the development of test-beds that simulate electrical charge generation of the energy harvesting power sources during the firing and the flight. These test-beds provide the means to test the conversion electronics in realistic conditions and to conduct further studies of the internal structure and design of storage medium. Results of tests with the energy conversion electronic circuitry developed for different applications using the above firing and flight simulation test-beds are presented. A discussion is also presented on the methods to improve energy conversion efficiency and high-G survivability for operation in harsh gun-launch environment.

9059-10

Preparation and characterization of thick films PU/PZT for energy harvesting

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(Micro-Electro-Mechanical-Systems), progressively invading the market, with applications in many fields, such as aerospace, medicine and industry. One of the aims of these microstructures is to allow the deployment of autonomous sensor networks, that is to say a set of systems that collect information from their environment, process, transmit and interact between them, and this, without human intervention. To make these energy autonomous systems and therefore do not use batteries which have a limited life since it will at one time or another to recharge or replace, it is possible to recover energy from ambient vibrations to using piezoelectric systems. Electrostrictive polymers are a novel class of electro-active polymers (EAPs) that recently became the object of considerable research efforts due to their actuation properties. The latest studies demonstrate the possibility of harvesting mechanical energy using these materials. Electro-active polymers (EAPs) exhibit significant advantages compared to piezoelectric ceramics; they are lightweight, flexible, ductile, low-cost, with a high strength-to-weight ratio, a good processability, and a low mechanical impedance. The *drawback of using electrostrictive polymers for energy harvesting concerns the fact that a bias voltage is required for working in the pseudo-piezoelectric mode. To develop micro-generators, it is necessary that another electroactive material produces the static electric field.

The topic of this abstract is to propose new materials for harvesting energy using electrostrictive polymers. The energy harvesting of Polyurethane/Lead Zirconate Titanate composites, has been investigated. Volume fraction of 50%, 60%, 70% and 80% of PZT was used to prepare thick films of 40-80µm of thickness by doctor blad technical. Energy harvesting tests, for the films at very low frequency and deformation, and without application of any electrical current, gives 5 mA of current harvested. These results, make a difference between the literature, where it must be use a initial statically current to recover the same value of energy from PU.

9059-11

Power optimization technique using frequency tuning concept for cantilever piezoelectric energy harvester

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No Abstract Available

9059-12

Model for friction and wear reduction through piezoelectrically-assisted ultrasonic lubrication

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Friction forces between two sliding surfaces can be reduced by superimposing ultrasonic vibrations onto the sliding velocity. This phenomenon is often referred to as ultrasonic lubrication. Often related to friction, wear is the displacement of materials from one or both surfaces in contact during sliding. Studies have been conducted in ultrasonic friction and wear reduction between metals. This article investigates the effect of ultrasonic vibrations on friction and wear reduction for various material combinations, including metals and non-metallic materials.

A modified tribometer was designed and built for pin-on-disc friction and wear tests. The pin consists of a piezoelectric actuator and an acorn nut. The actuator generates ultrasonic vibrations of 2.5 µm at 22 kHz in the direction perpendicular to the disc surface. The pin is held by a gymbal assembly, which is also used for applying various normal loads and measuring friction forces. A disc is held in contact with the pin by a lathe chuck, which is driven by a motor. Different levels of rotating speeds, radii and testing durations are chosen to obtain various linear speeds, total revolution counts and travel distances. An optical profilometer is employed to measure the profiles of the wear grooves as well as the volume loss of the disc. Scanning electron microscopy is utilized to investigate the wear groove surfaces at microscopic scales. The dependence of friction and wear reduction on linear speeds, distances, and normal loads is studied. An analytical model is proposed to explain the experimental results.

9059-13

Application of active camber morphing concept based on compliant structures to a regional aircraft

Sergio Ricci, Alessandro De Gaspari, Politecnico di Milano (Italy)

The present work addresses the assessment of the potential benefits that an active camber morphing can bring in terms of performances when applied to a Regional Aircraft. The subject of the work is part of the FP7-NOVEMOR project (Novel Air Vehicle Configurations: From Fluttering Wings to Morphing Flight) which is one of the many projects from the seventh European Framework Programme. The Reference Aircraft (RA) here considered is representative of a typical regional jet capable to carry 113 PAX in a single economic class and provide operational flexibility to fly different missions at the transonic regime. It was designed by Embraer, one of the partners of NOVEMOR project. The implementation of active camber concept is based on the use of conformable morphing control surfaces. Aiming at the optimal design of such as morphing devices, two dedicated tools called PHORMA and MORFEO, respectively, are introduced. The definition of the optimal shape taking into account both aerodynamic and structural constraints is done by PHORMA. Then MORFEO, based on the load path approach codified by coupling a non linear beam solver to a genetic multi-objective optimizer, is adopted to generate the optimal internal structure able to produce, when loaded, the target optimal shape. The optimization is performed on a set of sections along the wing then the full 3D wing is obtained using PHORMA, by lofting the optimal 2D solutions.

Details of the adopted approach as well of the obtained results will be included into the final paper.

9059-14

A study on dynamics of submerged pipe with side supports and flange

Hwee Kwon Jung, Gyuhae Park, Jang Won Seo, Chonnam National Univ. (Korea, Republic of)

This paper presents vibration testing, control, and finite element analysis of a piping system, which is subjected to the changes in fluid levels. Nuclear power plants typically employ a cooling system that uses sea water. These systems are subjected to dynamic characteristic changes caused by sea-level variations, which introduces failures of cooling system components. Therefore in this study, analytical and experimental studies were performed to understand the effect of sea-level changes on the dynamic characteristics of piping systems. It was shown that, as the sea-level increases, pipe's natural frequencies decreases in relation to its mode shape. A 1/14 scale model was also built to compare the results obtained by the analytical study. A good agreement between experiment and analytical studies were observed. Finally, an on-line resonant frequency identification system was proposed and developed, which utilizes piezoelectric transducers as sensors and actuators, in order to avoid catastrophic failure of piping systems.

9059-15

Epoxy microcrack density tracking in composite overwrapped pressure vessels using embedded FBGs

Scott M. Strutner, Univ. of California, Los Angeles (United States); Francisco Pena, California State Univ., Los Angeles (United States); Anthony Piazza, Allen R. Parker Jr., W. Lance Richards, NASA Dryden Flight Research Ctr. (United States); Gregory P. Carman, Univ. of California, Los Angeles (United States)

This study reports on signal recovery of optical fiber Bragg gratings embedded in a carbon fiber composite overwrapped pressure vessel's (COPV) structure. COPVs are commonly used for the storage of high pressure liquids and gases. They utilize a thin metal liner to seal in contents, with a composite overwrap to strengthen the vessel with minimal additional mass. This COPV is instrumented with surface mounted and embedded fiber Bragg gratings (FBGs) for strain sensing. FBGs have been studied as strain sensors for the last couple decades. This study uses optical frequency domain reflectometry (OFDR) to sub-divide FBGs for multiple strain measurements within each Bragg grating. Many embedded sensors report a multi-peak, chirped response which is not able to be interpreted by current algorithms. As loading increases, so does the number of chirped FBGs. When these are sub-divided using OFDR, the chirped gratings' strains along their length are recovered, and show a high strain difference across each FBG. This study reports on this success, and shows methods to quantify when the signal is not chirped, and needs no further sub-division. The high strain rate across each chirped FBGs shows strain concentrations, which may be from microcracks in the epoxy matrix. Matrix microcracks are a precursor to more serious damage mechanisms, particularly delamination. Tracking microcrack density would be an early detection method in structural health monitoring. Further testing using pseudo-continuous FBGs embedded in a COPV's composite structure is required to create a robust structural health metric from the recovered embedded FBGs' signals.

9059-16

Evaluation of embedded FBGs in composite overwrapped pressure vessels for strain based structural health monitoring

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The increased use of composite overwrapped pressure vessels (COPVs) in space and commercial applications, and the explosive nature of pressure vessel ruptures, make it crucial to develop techniques for early condition based damage detection. The need for a robust health monitoring system for COPVs is a high priority since the mechanisms of stress rupture are not fully understood. Embedded Fiber Bragg Grating (FBG) sensors have been proposed as a potential solution that may be utilized to anticipate and potentially avoid catastrophic failures. The small size and light weight of optical fibers enable manufactures to integrate FBGs directly into composite structures for the purpose of structural health monitoring. A challenging aspect of embedding FBGs within composite structures is the risk of potentially impinging the optical fiber while the structure is under load, thus distorting the optical information to be transferred. As the COPV is pressurized, an embedded optical sensor is compressed between the expansion of the inner bottle, and the outer overwrap layer of composite. In this study, FBGs are installed on the outer surface of a COPV bottle as well as embedded underneath a composite overwrap layer for comparison of strain measurements. Experimental data is collected from optical fibers containing multiple FBGs during incremental pressurization cycles, ranging from 0 to 10,000 psi. The graphical representations of high density strain maps provide a more efficient process of monitoring structural integrity. Preliminary results capture the complex distribution of strain, while furthering the understanding of the failure mechanisms of COPVs.

9059-22

Damper-controlled switch for SMA motion smoothing

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While the use of SMA-actuated devices continues to grow in many industries, current device limitations pose a challenge to successful adoption for certain classes of applications. SMA-actuated devices typically demonstrate motion with non-constant velocity due to non-linear thermo-mechanically coupled behavior of SMA material transformation, and motion sensitivity to external factors such as load, voltage, and ambient temperature. This variation in motion can lead to the perception of poor device quality, resulting in SMA-actuated devices to be limited to applications hidden from the sight of the product user, or augmented with higher cost controls to improve the motion quality. Therefore, a need exists for simple, passive, low-cost device technologies that enable the designer to prescribe desired motion characteristics with relative insensitivity to fluctuation in operating conditions. This paper presents a damped switch mechanism that delivers constant velocity and relative insensitivity to operating conditions when combined with a standard SMA wire actuator. The mechanism includes a damper that acts against a spring to open a switch when the velocity exceeds a tunable threshold; the desired speed can be set by choosing the preload of the speed-threshold spring. To validate the ability of the mechanism to provide the desired motion quality, experiments were conducted comparing the normal motion of the SMA actuator to the motion produced when the same actuator was fitted with a prototype of the damped switch mechanism. The addition of the damped switch mechanism produced nearly constant actuator velocity, performing significantly better than the SMA actuator alone. The tunability of the mechanism was demonstrated by using the speed-threshold spring preload to adjust the actuator velocity, producing a wide range of attainable constant velocities. Finally, a set of experiments was conducted to explore the mechanism's sensitivity to commonly fluctuating external factors such as load, voltage, and ambient temperature. Test results indicated low sensitivity to a wide range of operating parameters for which the operating limits were identified. The damped switch mechanism represents a simple, compact technology based on passive, low-cost components, providing a very practical solution that enables further integration of SMA-actuated devices into a broader class of applications.

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9060-1

Nonlinear plasmonics with Kerr-like media for sensing *(Keynote Presentation)*

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Sensing technologies are currently needed more for better maintainability, reliability, safety, and monitoring small variable changes on microscopic and nanoscale systems. Plasmonic sensor research has contributed to chemical and biological sensing needs by monitoring ultrafast temporal and spatial changes in optoelectronic systems. Nonlinear plasmonic waveguides with subwavelength confinement can further enhance the capabilities of plasmonic devices. In this study, we derive the full –vector Maxwell Equations for the single metal- dielectric slot waveguide and the metal –dielectric –metal waveguide with the dielectric having a Kerr-like nonlinearity. These waveguides typically have metallic losses that compete with nonlinearity at certain frequencies that can hinder surface plasmon wave propagation. By considering temporal and spatial beam propagation in these waveguides one expects to observe novel effects that could be used for sensing applications such as femtosecond pulse propagation with plasmon self-focusing, self-trapping, and frequency conversion with reduction in metallic losses. In addition, using Maxwell's Equations a theoretical model of a tampered waveguide or metal bulk with a triangle grooved nonlinear Kerr dielectric interior is presented to show stronger field enhancements with increased propagation length compared to the previous slot waveguides in this study. Furthermore, Finite Difference Time Domain (FDTD) and Pseudo–spectral methods are used to numerically solve Maxwell's Equations to simulate the previously described waveguide configurations.

9060-2

Metallic single-walled, carbon-nanotube-based temperature sensor *(Invited Paper)*

Kaji Muhammad M. Mohsin, Yaser Mohammadi Banadaki, Ashok Srivastava, Louisiana State Univ. (United States)

A metallic single-walled carbon nanotube (SWCNT) has been proposed as a highly sensitive temperature sensor with consideration of self-heating induced scattering. This sensor can be implemented to sense temperature spanning from 20º C to 400º C with high temperature coefficient of resistance (TCR) varying from 0.0035/ ºC to 0.009/ ºC. The basic structure consists of a metallic SWCNT over a silicon dioxide substrate with metal end contacts. Bias voltage of 0.1V has been applied in between these two contacts. For resistivity calculation, we have utilized one dimensional semi-classical transport model assuming SWCNT is perfectly conducting. The heat flow equation has been solved assuming steady state flow of heat, and contact and substrate are in thermal equilibrium with the surroundings. We have studied CNT sensor with different lengths and chiralities. The results show that resistance of longer (3µm) and thinner (9,0) CNTs increases rapidly with the increase in temperature. For a 3µm long SWCNT with chirality index (9, 0), TCR has the maximum value close to 0.009/ ºC. Since self-heating significantly affects electro-thermal transport; incorporation of this phenomenon enables us to design and model ambient temperature sensor accurately.

9060-3

Small-area low-power decimators for delta-sigma video sensors

Erika Azabache Villar, Alireza Mahmoodi, Orit Skorka, Dileepan Joseph, Univ. of Alberta (Canada)

A delta-sigma, or sigma-delta, analog-to-digital converter (ADC) comprises both a modulator, which implements oversampling and noise shaping, and a decimator, which implements low-pass filtering and downsampling. Whereas these ADCs are ubiquitous in audio applications, their usage in video applications is emerging. Because of oversampling, it is preferable to integrate delta-sigma ADCs either at the column or the pixel level of megapixel video sensors. Moreover, with column or pixel-level applications, area usage and power consumption per ADC are much more important than with chip-level applications, where there is only one or a few ADCs per chip. Recently, a small-area low-power decimator was presented that is suitable for both column and pixel-level applications. However, though the pixel-level design is small enough for invisible-band video sensors, it is too large for visible-band ones. As shown here, nanoscale CMOS processes offer a solution to this problem. Given constant specifications, small-area low-power decimators are designed, simulated, and laid out, full custom, for 180, 130, and 65 nm standard CMOS processes. Area usage and power consumption of the whole decimator, as well as a breakdown by component, are analyzed to establish a roadmap for the design and demonstrate that it will eventually be suitable for visible-band video sensors. Finally, given that the design has previously been published only in the patent record, this paper reviews its principal innovations, which have enabled significant area and power reductions over the prior art, in non-legal terms. Such decimators are expected to feature in emerging delta-sigma video sensors.

9060-4

Oxygen sensing glucose biosensors based on alginate nano-micro systems

Rashmi D. Chaudhari, Abhijeet Joshi, Rohit Srivastava, Indian Institute of Technology Bombay (India)

Aim: Clinically glucose monitoring in diabetes management is done by point-measurement. However, an accurate, continuous glucose monitoring, and minimally invasive method is desirable. The research aims at developing fluorescence-based glucose detecting biosensors based on near-infrared radiation (NIR) oxygen sensitive dyes.

Methods: Biosensors based on Glucose oxidase (GOx)-Rudpp loaded alginate microspheres (GRAM) and GOx-Platinum-octaethylporphyrin (PtOEP)–PLA-alginate Nano-in-Micro system (GPAM) were developed using air-driven atomization and characterized using optical microscopy, TEM, CLSM, fluorescence spectro-photometry etc. Biosensor performance and validation was done by exposing standard solutions of glucose. In-vitro biocompatibility was assessed using SRB-assay using L929 mouse fibroblast cell lines.

Results: Uniform sized GRAM and GPAM with size 50±10µm were formed using atomization. TEM images showed spherical nanoparticles of size of 200±50nm and 150±50nm for PLA nanoparticles and PtOEP-PLA nanoparticles. CLSM imaging of biosensors suggests that Rudpp and PtOEP-PLA nanoparticles are uniformly distributed in alginate microspheres. The GRAM and GPAM showed a good regression constant of 0.974 and of 0.9648 over a range of 0-10 mM of glucose with a high sensitivity of 3.349%/mM (625 nm) and 2.38%/mM at 10 mM of glucose for GRAM and GPAM biosensor. % Cell viability of both biosensors was

found to be acceptable (> 80%) with an edge of PtOEP over Rudpp owing to its NIR emission at 645 nm.

Conclusions: GRAM and GPAM biosensors show great potential in development of an accurate and minimally invasive glucose biosensor. NIR dye based assays can aid sensitive, minimally-invasive and interference-free detection of glucose in diabetic patients.

9060-5

Boron nitride nanotube: synthesis and applications *(Keynote Presentation)*

Catharine Fay, NASA Langley Research Ctr. (United States)

Since the advent of carbon nanotube (CNT) in 1991, scientists predicted that carbon's immediate neighbors on the periodic chart, boron and nitrogen, may also form perfect nanotubes. First proposed [1] then synthesized [2] by researchers at UC Berkeley in the mid 1990's, the boron nitride nanotube (BNNT) has proven very difficult to make until now. This presentation will describe the discovery of a new catalyst-free method for synthesizing highly crystalline, very long, and small diameter BNNTs using a high power laser under a high pressure and high temperature environment [3]. Progress in purification methods, dispersion studies, BNNT mat formation, modeling and diagnostics will also be presented. The white BNNTs offer extraordinary properties including neutron radiation shielding, piezoelectricity, thermal oxidative stability (>800˚C in air), and mechanical strength and toughness. The characteristics of the novel BNNTs and BNNT polymer composites and their potential applications are discussed.

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9060-6

A new low-cost, thick-film metallization transfer process onto PDMS using a sacrificial copper seed *(Invited Paper)*

Daniel D. Hilbich, Simon Fraser Univ. (Canada); Ajit Khosla, Concordia Univ. (Canada); Bonnie L. Gray, Simon Fraser Univ. (Canada); Lesley Shannon, Simon Fraser University (Canada)

We present a new low cost microfabrication technology enabling fully embedded thick film electroplated copper microstructures in polydimethyl siloxane (PDMS) utilizing a sacrificial conductive paint transfer method. The process begins with the deposition of a uniform sacrificial copper seed layer (Caswell Canada Copper Conductive Paint) onto a silicon or glass substrate via airbrushing. A dry film photoresist layer (DuPont Riston MM540) is then laminated onto the seed using a hot roll laminator and patterned using photolithographic techniques. After development, the seed layer is electroplated through the photoresist mask to achieve the desired copper thickness, followed by photoresist stripping. PDMS is then spin coated onto the electroplated copper pattern. The substrate is baked at 90°C via hotplate for 30 seconds, releasing the electroplated copper from the seed layer and permanently embedding it into the cured PDMS without cracking or otherwise deforming. We have performed initial characterizations of the embedded copper microstructures in terms of feature size, film thickness, surface roughness, resistivity, and reliability under flexing and stretching. Initial results show that we can achieve films 10µm to 50µm in thickness, with reliable feature sizes down to 100µm, and a film resistivity of approximately 265µ?•cm. We compare our results with existing thick film metal on PDMS processes, outline process variants such as adapting to use large scale substrates without a cleanroom facility, and discuss potential applications such as flexible microcoils and implantable metallized PDMS microcapacitors.

9060-7

Synthesis and characterization of graphene/cellulose nanocomposite

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Organic-inorganic hybrid composite have many benefit by adapting advantages of organic materials and inorganic materials. Cellulose is a well-known renewable material, which is environmentally friendly, biocompatible, cheap and lightweight. Graphene is one of the crystalline forms of carbon, one-atom thick layer of the layered graphite that has high electron mobility. Thus, cellulose and graphene hybrid composite has many advantages in terms of environmentally friendly, cheap as well as unique mechanical and electrical behavior. This paper introduces the fabrication process of graphene/cellulose nanocomposite film. Graphene/Cellulose nanocomposite films are prepared by mixing and stirring Functionalized Graphene (F-Graphene) into cellulose solution with N, N-dimethylacetamide (DMAc) and N,N´-carbonyldiimidazole (CDI), then casting the solution onto glass. This paper will report the mechanical and electrical behavior of graphene/cellulose nanocomposite. The morphology is investigated by scanning electron microscopy (SEM). The chemical bonding is investigated using Fourier transform infrared spectroscopy (FT-IR) and Raman spectra. The structural crystality is studied by X-ray diffraction (XRD) of the film. The comparison of electrical and mechanical properties between cellulose and graphene/cellulose nanocomposite will be discussed.

9060-8

Electrically conductive and thermal properties of electrospun PAN based carbon nanofiber membranes

Fenghua Zhang, Zhichun Zhang, Yanju Liu, Jinsong Leng, Yongtao Yao, Harbin Institute of Technology (China)

Carbon nanostructures are emerging multifunctional materials for advanced polymer matrix composites because of their high strength, elastic modulus, thermal and electrical conductivity and relatively low density. Carbon nanofiber membranes as a promising materials is considered in lots of fields, such as the aerospace and automotive sectors, and filters, scaffolds and fuel cells for bio-medical and energy applications. In this paper, uniform nanofiber membranes with high electrically conductive property and thermal properties are successfully obtained from 10% polyacrilonitrile (PAN)/N, N-dimethylformamide (DMA) solution via electrospinning method. The resultant fibrous membranes are stabilized and carbonized to get carbon nanofiber membranes (thickness is 0.1mm). Scanning electron microscopy (SEM) was applied to investigate the morphology and structure of nanofiber membranes. The carbon nanofiber membranes expressed electrical conductivity varying from 7.85 to 12.30 S.cm-1 by adjusting the electrospinning technology. The electrically conductive properties were characterized by using four-point probe. The thermal reliability research have two main aspects: testing the distributed heat by multi-temperature measure instrument and the thermal analysis in the assistance of CAE software. The carbon nanofiber membranes can reach 200 ? with the applied voltage at 16 V. The temperature increased from room temperature to high temperature with the applied voltage increasing from 2 V to 20 V. In addition, the nanofibrous membranes can realize the quick electric driving within 10 seconds. It was significant to expand the technical potential for electrically conductive materials.

9060-9

Low-cost near-infrared measurement of subcutaneous fat for newborn malnutrition

Alistair L. McEwan, The Univ. of Sydney (Australia); Shuning Bian, The Univ. of Sydney (Australia) and The University of Oxford (United Kingdom); Gaetano Gargiulo, Univ. of Western Sydney (Australia); Robert Morhard, The Univ. of Sydney (Australia) and Swiss Federal Institute of Technology, Zürich (Switzerland); Peter Jones, Fatin Hamimi Mustafa, Emily Bek, Heather Jeffery, The Univ. of Sydney (Australia)

Low fat composition in newborns exposes them to an immediate risk of increased mortality and morbidity, and to diabetes and obesity diseases in later life. Information about nutritional and dietary status of newborns can be accessed by measuring the amount of fat composition in the body. The functions of subcutaneous fat involve energy storage, thermo-insulation and a physical buffer. The examples of current technologies for newborn body fat monitoring are a device based on air displacement plethesmography (PeaPod), dual-energy X-ray, and underwater weighting. However they are bulky, expensive, immobile, and require technical expertise. We propose measurement of in-vitro subcutaneous fat by diffuse reflectance measurement system. A three-layered tissue model mimicking the subcutaneous fat layer in newborns is introduced with a preliminary study to measure fat using dual-wavelength near-infrared light. Based on the output data from these measurements, we have proposed a transmission and scattering model. This model estimated the amount of reflected light collected by a photodetector after incident light is scattered in several fat layers. A low cost sensor, suitable for mass use in the developing world was developed. It consists of a single LED and two photodetectors (900nm and 1000nm). These were chosen to be sensitive to fat at its 930nm peak and water at 1000nm, to remove hydration bias. Results on a porcine tissue model demonstrate differentiation as low as 2mm fat which is a relevant screening thickness to indicate low percentage body fat.

9060-10

Development of an electrical and optical neural probe for neurotransmitter sensing in the brain

Hargsoon Yoon, Min H. Kim, Norfolk State Univ. (United States); Hyunjung Kim, National Institute of Aerospace (United States); Kyo D. Song, Norfolk State Univ. (United States); Laurie L. Wellman, Larry D. Sanford, Eastern Virginia Medical School (United States); Hae S. Kim, The College of William & Mary (United States); Sang H. Choi, NASA Langley Research Ctr. (United States)

As an essential neuro-device technology for clinical treatments, we designed and integrated electrical and optical sensing probes into an optrode which has a carbon fiber and two optical fibers to measure dopamine concentration in the brain. Fast scan cyclic voltammetry is used to electrochemically measure dopamine concentration. Two different optical fiber designs are employed for optical stimulation and sensing purposes. Additionally, optical sensing responses are synchronized with electrochemical sensing and their correlation is examined. We describe the use of these sensors in rat brain and will discuss key design parameters of in-vivo electrical and optical sensing in neural tissue.

9060-11

Nano-electrode array for in-vivo action potential recording in the brain

Darryl W. Scott, Min H. Kim, Camille Cooper, Hargsoon Yoon, Norfolk State Univ. (United States)

The development of microelectrodes for neural recording devices is important to better understanding the brain and how it communicates with the body. The purpose of this research is to develop a method to improve the quality of the retrieved signal and enhance biocompatibility. We are developing a neural probe with nano-electrode array on a flexible polymer substrate. To increase the quality of the signal the implementation of vertically aligned nanowires on the electrodes will be used to increase surface area and improve electrochemical impedance for recording. In theory by growing nanowires in the contacts of our neural probe we can increase the surface area for action potential recording and therefore obtain a higher quality and more accurate signal. Tissue encapsulation was addressed by using biocompatible materials and a flexible substrate enabling minimization of immune response to the implantation of a foreign object into the body. Through the processes of electroplating and photolithography, the nanowire structures were imbedded into the probe structure. In this presentation, in-vivo recording after implantation of the neural probe into the rat brain is discussed.

9060-12

Neural activity-based biofeedback therapy for autism spectrum disorder through wearable wireless textile EEG monitoring system

Ahna Sahi, Sam Higginbottom Institute of Agriculture, Technology and Sciences (India); Pratyush Rai, Sechang Oh, Mouli Ramasamy, Vijay K. Varadan, Univ. of Arkansas (United States); Robert E. Harbaugh, The Pennsylvania State Univ. (United States) and Penn State Milton S. Hershey Medical Ctr. (United States)

Mu waves, also known as mu rhythms, comb or wicket rhythms are synchronized patterns of electrical activity involving large numbers of neurons, in the part of the brain that controls voluntary functions. Controlling, manipulating, or gaining greater awareness of these functions can be done through the process of Biofeedback. Biofeedback is a process that enables an individual to learn how to change voluntary movements for purposes of improving health and performance through the means of instruments such as EEG which rapidly and accurately 'feedback' information to the user. Biofeedback is used for therapeutic purpose for Autism Spectrum Disorder (ASD) by focusing on Mu waves for detecting anomalies in brain wave patterns of mirror neurons. Conventional EEG measurement systems use gel based gold cup electrodes, attached to the scalp with adhesive. It is obtrusive and wires sticking out of the electrodes to signal acquisition system make them impractical for use in sensitive subjects like infants and children with ASD. To remedy this, sensors can be incorporated with skull cap and baseball cap that are commonly used for infants and children. Textile based multi-electrode EEG, EOG and EMG monitoring system with embedded electronics for data acquisition and wireless transmission has been seamlessly integrated into these items for continuous detection of Mu waves. Textile electrodes were placed on positions C3, CZ, C4 according to 10-20 international system and their capability to detect Mu waves was tested. The system is ergonomic and can enable early diagnosis in infants and planning therapy for ASD patients.

9060-13

Wireless sleep monitoring headband to identify sleep and track fatigue

Mouli Ramasamy, Sechang Oh, Vijay K. Varadan, Univ. of Arkansas (United States)

Detection of sleepiness and drowsiness in human beings has been a daunting task for both engineering and medical technologies. Accuracy, precision and promptness of detection have always been an issue that has to be dealt by technologists. Commonly, the rudimentary bio potential signals – ECG, EOG, EEG and EMG are used to classify and discriminate sleep from being awake. However, the potential drawbacks may be high false detections, low precision, obtrusiveness, aftermath analysis, etc. To overcome the disadvantages, this paper proposes the design of a wireless and a real time monitoring system to track sleep and detect fatigue. This concept involves the use of EOG to measure the blink rate and asses the person's condition. In this user friendly and intuitive approach, EOG signals are obtained by the dry gold wire nano-sensors fabricated on the inner side of a flexible headband. The acquired signals are then electrically transmitted to the data processing and transmission unit, which transmits the processed data to the receiver/monitoring module through WCDMA/GSM communication. This module is equipped with a software program to process, feature extract, analyze, display and store the information. Thereby, immediate detection of a person falling asleep is made feasible and, tracking the sleep cycle continuously provides an insight about the experienced fatigue level. The novel approach of using a wireless, real time, dry sensor on a flexible substrate reduces the obtrusiveness, and techniques adopted in the electronics and software facilitates and, substantial increase in efficiency, accuracy and precision.

9060-32

A graphene field effect transistor for high temperature sensing applications *(Invited Paper)*

Yaser Mohammadi Banadaki, Kaji Muhammad M. Mohsin, Ashok Srivastava, Louisiana State Univ. (United States)

Graphene is a promising material for sensor applications due to its high electrical and thermal conductivity. In this work, we have explored the feasibility of a thin oxide back-gated graphene field effect transistor (G-FET) as a temperature sensor. The oxide thickness, width and length of the graphene channel are 1nm, 100nm and 500nm, respectively. The resistivity of the device has been calculated using the semi-classical transport equations considering quantum capacitance of thin gate oxide. Phonon scattering of electrons in graphene channel of the transistor has been considered in calculating saturation and drift velocities. The generated self-heating in graphene-silicon dioxide interface, silicon dioxide layer, and back-gated silicon wafer has been also considered in resistivity calculation.

We have found that the resistivity of G-FET is highly sensitive to high ambient temperature variation. The temperature coefficient of resistance (TCR) has been calculated at room temperature and high temperature (400C) for different gate voltages, which shows TCR variation from 2.5?10-5 to 5.35?10-3 per degree centigrade. The change in resistivity of G-FET can be best examined as a third order dependence on the ambient temperature from 0 to 400C for gate-source voltages from 0 to 5V exhibiting the highly sensitive resistance to high temperature variation. In order to investigate the sensitivity of G-FET to gate and drain bias voltages, the TCR values have been calculated at high temperatures (390C to 400C). The TCR values are highest for low drain to source voltages and high gate to source voltages, which shifts TCR to lower values by increasing drain to source voltages.

9060-15

CMOS digital pixel sensors: technology and applications *(Keynote Presentation)*

Orit Skorka, Dileepan Joseph, Univ. of Alberta (Canada)

Image sensors can be found in a wide range of applications that cover the entire electromagnetic spectrum, from gamma ray to terahertz. Portable digital cameras can now be purchased at a reasonable cost for invisible bands, in which imaging systems used to be expensive and complex and, therefore, had limited application. The global image sensor market is also growing. 3D integrated circuit (IC) technologies, based on vertical integration of active devices, are emerging. They are advantageous for heterogeneous microsystems, such as invisible-band image sensors, and can significantly improve performance. Typically, with either charge coupled device (CCD) or complementary metal-oxide-semiconductor (CMOS) technology, image sensors are based on analog pixels, especially for visible-band applications. However, transition to digital pixels is inevitable, particularly with the development and availability of nanoscale CMOS processes. With CCD arrays, data conversion is done at board level, i.e., off chip. With CMOS active pixel sensor (APS) arrays, data conversion is done either at chip level or column level. With CMOS digital pixel sensor (DPS) arrays, data conversion is done at pixel level, and the output of each pixel is a digital signal instead of an analog one. Compared to analog pixels, digital pixels are much more immune to noise, which enables higher peak signal-to-noise ratio, lower dark limit, and wider dynamic range. However, digital pixels need to accommodate a large number of transistors. Therefore, DPS arrays are especially suitable for invisible-band applications, where larger pixels are acceptable, and are mainly practical with emerging 3D IC technologies.

9060-16

Molecular dynamics study of phonon screening in graphene *(Invited Paper)*

Brahmanandam Javvaji, D. Roy Mahapatra, S. Raha, Indian Institute of Science (India)

Theoretical lattice thermal conductivity of 10 µm long graphene for example is in the range of 1900 W/(m-K). Such a high thermal conductivity is mainly due to the homogeneous distribution of periodically arranged atoms and the absence of scattering centers for the heat carriers (phonons). However, ideal graphene properties cannot be invoked into quantum transport through a realistic device in which finite size effects and imperfections in the graphene lattice play important role. In order to simulate such realistic effects, graphene quantum dots or graphene nanoribbons with specified width are introduced. Graphene lattice in different orientations (armchair and zigzag) and passivation of the cut regions by hydrogen is possible. Such graphene quantum dots show size dependent properties in contrast to the regular graphene. In this work, we are interested in identifying the phonon blocking in graphene with graphene quantum dots. Phonon blocking is analyzed from lattice thermal conductivity of graphene quantum dot system. The zigzag edges of the quantum dot are passivated with hydrogen and the armchair edges are connected to the graphene. The lattice thermal conductivity is calculated using real space Green's function technique. This technique uses the velocity auto-correlation function, where the required atomic velocity information is generated using molecular dynamics simulations. In addition to this, we have also studied the phonon dispersion characteristics of the graphene quantum dots, which helps in understanding the possible excitations of phonon frequencies by electromagnetic field.

9060-17

A dual-function electronic module for chronic neural sensing and optogenetic stimulation

Min H. Kim, Norfolk State Univ. (United States); Young Kee Ryu, Sun Moon Univ. (Korea, Republic of); Hargsoon Yoon, Norfolk State Univ. (United States); Ilho Nam, Old Dominion Univ. (United States); Darryl W. Scott, Norfolk State Univ. (United States); Larry D. Sanford, Eastern Virginia Medical School (United States)

The development of miniaturized data acquisition and control systems is essential for advancing neuroscience research. In this project, we introduce a prototype system to record action potentials and perform pulsed optical stimulation locally in the brain of research animals. The system contains a microcontroller, an analog to digital converter, and electrical and optical stimulation drivers for pulsed width modulation control. In this presentation, the device prototype will be described and test results and design parameters will be discussed in terms of the temporal resolution of data acquisition and pulsed modulation control for optogenetic stimulation.

9060-18

Antibacterial polyelectrolyte-coated Mg alloys for cardiovascular applications

S. Seraz, Ramazan Asmatulu, Zheng Chen, M. Ceylan, Anil Mahapatro, Shang-You Yang, Wichita State Univ. (United States)

The present study deals with two biomedical subjects: corrosion rates of polyelectrolyte-coated magnesium (Mg) alloys, mainly used for biomedical purposes, and antibacterial properties of these alloys. Thin sheets of the Mg alloys were coated with cationic polyelectrolyte chitosan (CHI) and anionic polyelectrolyte carboxymethyl cellulose (CMC) using a layer-by-layer coating method, and then embedded with antibacterial agents under vacuum. Electrochemical impedance spectroscopy was employed to analyze these samples in order to detect their corrosion properties at different conditions. In the electrochemical analysis section, a corrosion rate of 72 mille inches per year was found in a salt solution for the sample coated with a 12 phosphonic acid self-assembled monolayer and 9 CHI/CMC multilayers. In the antibacterial tests, gentamicin was used to investigate the effects of the drug embedded with the coated surfaces against the Escherichia coli (E. coli) bacteria. Antibacterial studies were tested using the disk diffusion method. Based on the standard diameter of the zone of inhibition chart, the antibacterial diffusion from the surface strongly inhibited bacterial growth in the regions. The largest recorded diameter of the zone of inhibition was 50 mm for the pre-UV treated and gentamicin-loaded sample, which is more than three times the standard diameter. This study may open up new possibilities to develop antibacterial surfaces for various cardiovascular applications (e.g., stent, bone fixation plates/screws/wires, etc.).

9060-19

Efficient heart beat detection using embedded system electronics

Mouli Ramasamy, Sechang Oh, Vijay K. Varadan, Univ. of Arkansas (United States)

The present day bio-technical field concentrates on developing various types of innovative ambulatory and wearable devices to monitor several bio-physical, physio-pathological, bio-electrical and bio-potential factors to assess a human body's health condition without intruding quotidian activities. One of the most important aspects of this evolving technology is monitoring heart beat rate and electrocardiogram (ECG) from which many other subsidiary results can be derived. Conventionally, the devices and systems consume a lot of power since the acquired signals are always processed on the receiver end. Because of this back end processing, the unprocessed raw data is transmitted resulting in usage of more power, memory and processing time. This paper proposes an innovative technique where the acquired signals are processed by a microcontroller in the front end of the module and just the processed signal is then transmitted wirelessly to the display unit. Therefore, power consumption is considerably reduced and clearer data analysis is performed within the module. This also avoids the need for the user to be educated about usage of the device and signal/system analysis, since only the number of heart beats will displayed at the user end. Additionally, the proposed concept also eradicates the other disadvantages like obtrusiveness, high power consumption and size.

9060-20

Smart insole sensors for sports and rehabilitation

Tarmo Tamm, Univ. of Tartu (Estonia)

A light-weight, soft, robust and low cost sensory system integrated into the inner soles of footwear is being developed that channels information to a mobile device, allowing to assess the ergonomics of the technique applied and to achieve improved performance in several fields of sport. Being not limited to sports, such devices can be used for developing novel orthopedic footwear , help with rehabilitation after injuries, and preventing diabetes-related limb problems as elevated plantar pressures are an important predictor of diabetic foot ulceration.

The applicability of several types of potential sensory materials, including resistive, capacitative, piezo-electric, piezo-resistive, and electroactive polymers is discussed. Several benefits and shortcomings of each material class were identified. In order to obtain thin devices and to ensure manufacturability, the present approach is based on various laminate materials. Response time, hysteresis, creep, reproducibility, signal to pressure linearity, and other parameters will also be discussed. The focus of athletes (accurate high frequency force measurements under different conditions) and those of medicine (stability, reliability, lifetime) are somewhat different, requiring careful optimization of the approaches. The supporting electronics need to be light-weight, small footprint and have low power consumption as well. Naturally, the data from the insole has to be transmitted wirelessly. Other key elements of an appropriate design are the sizing of individual sensors, optimizing the elastic modulus of the laminate layers, obtaining sufficient mechanoelectrical performance, and creating isolation from the surrounding environment in order to minimize the influence of wear and moisture.

9060-21

Non-destructive examination system of vitreous body

Takuma Shibata, Jin Gong, Yosuke Watanabe, Md. Hasnat Kabir, Masato Makino, Hidemitsu Furukawa, Yamagata Univ. (Japan)

Eyeball plays a quite important role in acquiring vision. Vitreous body occupies the largest part in the eyeball and consists of biological, elastic, transparent, gel like materials. In the present medical examination, the non-destructive examination method of the vitreous body has not been established. Here we focus on an application of dynamic light scattering to this topic. We try to apply our lab-made apparatus, scanning microscopic light scattering (SMILS), which was specially designed for observing the nanometer-scale network structure of gel materials. We also try to implement the SMILS technology to a commercial apparatus, nano-Partica (Horiba Co., Ltd.), in order to examine the vitreous body. The principle of nano-partica is the same as SMILS, but it is not possible to measure the gel because the ensemble averaged cannot be obtained from the nano Partica. In this regard, we customized the nano Partica

both in hardware and in software. By using both the SMILS and the customized nano-Partica, we successfully examined the Latex and the vitreous bodies of healthy pigs. From the measurement results, it is proved that both systems are able to measure the mesh size in non-destructive way. We discuss the changes in mesh size by collecting terms of the Vitreous body. In particular, we discuss the changes in mesh size (cutter size, speed) by the conditions at the time of collecting the vitreous body.

9060-22

Smart materials for smart microfluidic devices and instruments *(Keynote Presentation)*

Bonnie L. Gray, Simon Fraser Univ. (Canada)

As microfluidic systems evolve from "chip-in-the-lab" to true portable lab-on-a-chip (LoC) or lab-in-a-package (LiP) microinstrumentation, there is a need for increasingly miniaturized sensors, actuators, and integration/interconnect technologies. Furthermore, as microfluidic instruments are increasingly realized in polymer-based rather than glass or silicon based platforms, there is a need to realize these components in materials that are polymer-compatible. Smart materials such a stimuli-responsive hydrogels have been recognized for over a decade as being beneficial to the development of "smart microfluidics" systems and instrumentation. In addition, smart materials such as conductive and magnetic nanocomposite polymers can be employed to push microfluidics systems to greater degrees of portability, and/or flexibility for wearable/implantable systems. Conductive and magnetic polymers are realized by rendering the base polymer functional through the introduction of filler micro- and nano- particles with particular properties, potentially along with additional fillers to increase conductivity or uniformity of nanoparticle dispersion. Base polymers may include commonly employed microfluidics materials such as silicones, photoresists, and other thermosetting and thermoplastic polymers. Smart materials can be employed to realize electrodes, electronic routing, heaters, mixers, valves, pumps, sensors, and interconnect structures in polymer-based microfluidic systems. Stimuli for such smart materials can be realized and controlled on-chip or in a small package, thus greatly increasing the degree of portability and the potential for mechanical flexibility of such systems. This talk will discuss cutting edge research into smart materials as applied in particular to the sensors, actuators, and integration/interconnect schemes for microfluidic devices and instrumentation.

9060-23

Robust low-cost flexible touchpads using embedded conductive nanocomposite polymer

Alireza Rahbar, Mona Rahbar, Bonnie L. Gray, Simon Fraser Univ. (Canada)

We present the design and fabrication of a flexible array of switches that can be integrated with other wearable electronics and sensor devices. Each switch consists of 4 elements: fascia, target, spacer and a sensor coil. The user presses the fascia, bringing the target in contact to the sensor coil. Any change in the position of the target changes the coil inductance due to generation of eddy currents that can be detected by the electric circuit and the custom software. Contact between the target and coil also measurably changes the inductance of the coils. Different sizes and geometries (square, circular, hexagonal and octagonal) of coils have been investigated to determine which couple best with the conductive nanocomposite polymer that forms the target for the inductive coils. We describe techniques for patterning two-layer inductive coils on a flexible PCB, allowing us to achieve a coil trace thickness of 100µm. We also present a new low cost microfabrication technique to create the inductive flexible coils using embedded conductive nanocomposite polymer in polydimethylsiloxane (PDMS) as an alternative to flexible PCBs. Finally, we describe an electric circuit that accurately measures known inductances as low as 500nH and is used to detect the change in the inductance of the coil when the user presses the target element of the sensor. This change in inductance was measured to be 30% of its original value of 80uH for coils made with conductive nanocomposite polymer, showing high sensitivity.

9060-24

FITC-tagged macromolecule-based alginate microspheres for urea sensoring

Abhijeet Joshi, Rashmi D. Chaudhari, Rohit Srivastava, Indian Institute of Technology Bombay (India)

Aim: Urea is an important biomarker for identification of kidney diseases. Early urea detection using a specific and sensitive technique can significantly reduce the mortality of patients. The research aims at developing fluorescence-based FITC-mediated pH detection for urea measurement.

Methods: A co-immobilized system containing FITC-dextran and Urease in alginate microspheres was developed using air-driven atomization. The Urea biosensor was characterized using optical microscopy, SEM, CLSM, and encapsulation efficiency. Urea biosensing studies in both solution phase and suspension phase were performed by exposing different standard solutions and buffers containing urea using fluorescence spectroscopy ?ex=488 nm and ?em=520 nm. Urea biosensor performance was validated for accuracy, response time, linearity, range and reproducibility studies.

Results: The microspheres were found to be uniform and spherical in nature with sizes (50±10µ). CLSM scans showed FITC-dextran and Urease was uniformly distributed in the alginate microspheres. The encapsulation efficiency individually were >85% with most of the concentrations used. Solution phase urea sensing showed a linear range of 0-0.5mM at the tested concentrations of 0.5 and 1mg/ml of FITC-dextran and Urease, respectively. Urea biosensing studies in suspension phase indicate that a linear correlation was observed with increasing urea concentrations. The urea biosensing regression coefficient was 0.9878 in the linear range 0-50 mM. The Urea biosensor was found to be accurate and reproducible with an inter-day RSD of 5%.

Conclusions: FITC-dextran and Urease loaded alginate microspheres show a great potential for developing a urea biosensor for early detection of kidney diseases.

9060-25

Strain sensor based on cellulose ZnO hybrid nanocomposite

Hyun-U Ko, Gyu-Young Yun, Joo-Hyung Kim, Jaehwan Kim, Inha Univ. (Korea, Republic of)

ZnO is well known semiconductor material with high band gap as well as piezoelectricity. Because of its high performance of electromechanical behavior, ZnO based piezoelectric devices have taken great attention from many research groups. However, ZnO should be grown on a flexible substrate so as to allow flexibility. Since cellulose is renewable, flexible and biocompatible, ZnO is grown on cellulose by hydrothermal process, then a novel flexible piezoelectric material can be obtained. We report the fabrication and strain sensor behavior of cellulose ZnO hybrid nanocomposite(CEZOHN) which is one of novel piezoelectric material. In this research, simple piezoelectric strain sensor based on CEZOHN is made by directly stretching it and by boding it on a cantilever. Its performance is measured in terms of longitudinal and bending strain. This strain sensor demonstrate good sensitivity and linearly.

9060-26

Development of a flexible supercapacitor using iridium oxide nanowire and active carbon electrodes *(Invited Paper)*

Min H. Kim, Hargsoon Yoon, Norfolk State Univ. (United States)

Supercapacitor has taken a place between battery and capacitor due to its high energy density and large number of charging cycle. Especially flexible thin film supercapacitor has been widely studied because of versatility in many applications. In this research, iridium oxide as a cathode material was studied to improve the performance with active carbon as an anode. For high energy density, we implemented gold nano-wire electrodes coated with electrochemically deposited iridium oxide and increase surface area and charge storage capacity. As an anode of asymmetric supercapacitor structure, active carbon electrodes were applied due to its high porosity and conductivity. Various size of gold nano-wire with various thickness of iridium oxide was examined by cyclic voltammetry to find out design parameters for optimum performance and cost effectiveness.

9060-27

Paper like cellulose-ZnO hybrid nanocomposite and its photoelectrical behavior

Seongcheol Mun, Hyun-U Ko, Inha Univ. (Korea, Republic of); Bryan Kang, Samsung Electro-Mechanics (Korea, Republic of); Jaehwan Kim, Inha Univ. (Korea, Republic of)

Paper based composite with semiconductor nanomaterial is a fascinating orgnic-inorganic hybrid composite that has improved properties of flexibility, biocompatibility and functionality. Cellulose EAPap is one kind of paper electric device. To improve functionality of Electro-Active Paper (EAPap), ZnO is used as hybrid inorganic composition. Cellulose-ZnO hybrid nanocomposite (CEZOHN) is fabricated by seeding and growing ZnO on cellulose film with a simple chemical reaction. CEZOHN reveals not only electrical, eletromechanical behavior but also photoelectrical behavior. This paper reports specially photo-response and sensitivity of CEZOHN under several light source: UV light, sun and fluorescent light. The fabrication process is briefly introduced, and induced voltage, induced current under light source are investigated. Also, the ZnO effect of CEZOHN and its mechanism is studied and its possibility of application as photosensor, photodiode, photovoltaic device will be discussed.

9060-28

Present a new type of self-heating composite based on carbon nanotubes paper and investigate the feasibility in deicing

Hetao Chu, Zhichun Zhang, Yanju Liu, Jinsong Leng, Harbin Institute of Technology (China)

In this paper, a novel self-heating composite material utilizing carbon nanotubes (CNTs) paper is designed and fabricated successfully. The carbon nanotube paper was prepared by multiple steps of CNTs dispersion and suspension filtration as shown in Fig1. a and characterized by scanning electron microscopy thermo gravimetric analysis nitrogen adsorption isotherms at 77K and so on. The surface of the as-prepared CNTs paper is smooth and very flexible. The conductivity of the CNTs paper could be regulated from 30 S/cm to 200 S/cm. The fabricating process of the self-heating is shown in Fig.1 b and the electric heating performance under different ambient temperature, power changing from 4.3W to 44.8W and wind speed ranging from 8m/s to 14m/s was discussed. In addition, the feasibility of the application in the deicing of the composite was simulated by the software of Fluent. The thermal behavior was discussed combining the experimental and simulated values, especially the temperature field distribution under different wind speed. The maximum heating rate can reach 2?/s under different condition. The equilibrium temperature and energy consumption of the composite at different power compared with the commercial kanthal electric heating film were also investigated. The energy consumption of the self-heating material is less than the kanthal electric heating film to reach the same equilibrium temperature which may be caused by the difference of heat capacity. The experimental and simulated results indicate the electric heating performance of CNTs paper-based composite is superior to the commercial kanthal electric heating film and has feasibility in the field of deicing.

9060-29

Screen printed conductive nanoparticle composite polymer with applications to wearable ECG electrodes

Daehan Chung, Simon Fraser Univ. (Canada); Ajit Khosla, Concordia Univ. (Canada); Bonnie L. Gray, Simon Fraser Univ. (Canada)

Flexible electronics have the potential to offer the next major step in the evolution of electronic systems. The production of electronic components with flexible structures will enable the low-cost manufacturing of more compact, lightweight systems, as well as reduced environmental impact. Despite the enormous opportunity, a number of problems, such as limited conductivity or limited flexibility, exist with current flexible electronics technologies that have limited their market application especially in the wearable sensors area.

We have developed conductive nanoparticle composite polymers (NCPs) that possess both good conductivity and flexibility, and screen printed it on fabric to realize wearable flexible electrodes and electronic routing. The NCPs consist of dispersed silver nanoparticles (90~210nm) in a screen printable plastisol ink. The percolation threshold is 56 wt-%, and the resistivity of 1.9x10^-6 ohm-m was observed at 70 wt-% of Ag nanoparticles. To test the screen printed NCP's flexibility, we measured the resistivity of Ag NCPs (70wt-%) at different bending angles (-90° ~ 90°), and compared them. The maximum difference was 6.6% for forward bending and 3.3% for backward bending without electrical disconnection.

We have screen printed this Ag NCP on fabric to use them as wearable dry ECG electrodes. The sensing electrodes (3mm diameter circle) are chloridized to form Ag/AgCl electrodes and attached on a volunteer. We measured the ECG signal using the right-leg driven ECG circuit and could observe normal ECG signals with P-wave, clear QRS peaks, and T-wave even without applying electrolyte gel.

9060-30

Patterned nano-islands using solid-state dewetting with predefined temperature profiles

Ilwoo Seok, Shivan Haran, Arkansas State Univ. (United States)

The fabrication of patterned nano-sized island structures using solid-state dewetting of thin film is demonstrated. Laser source is used to provide thermal energy to thin film deposited onto silicon on insulator and this energy is converted to surface tension energy that will be driving force for dewetting of thin film and forming island structures. To pattern island structures with a designed shape, temperature profile is predefined on top of thin film wafer by means that laser source passes through a positive photo-mask which places on thin film wafer, which was designed

according to the desired shape. Successfully patterned nano-sized island structure is then observed through SEM and AFM. In this paper, simulation results on electromagnetic fields around the patterned nano-islands are also presented.

9060-56

Digital watermarking algorithm on tank's 3D mesh model based on DHartley transform

Qi Hu, Jilin Business and Technology College (China) and Changchun Univ. of Science and Technology (China); Lang Zhai, Jilin Business and Technology College (China)

With the growing popularity and application of 3D technology ,and 3D models for copyright protection also increases. So this application of digital watermarking technology, As DHartley transformation is the linear reversible transformation, the paper proposed a digital watermarking algorithm on tank's 3D mesh model based on DHartley transform. and made it loaded into the Vega real-time visual simulation system. In order to protect the originality of the 3D model. Firstly, put 3D model into affine transform, and take the distance from the center of gravity to the vertex of 3D object in order to generate a one-dimensional discrete signal; then make this signal into DHartley transform to change its frequency coefficients and embed watermark. Then the inverse transform to generate a 3D model with a watermark . In fixed affine space, achieve the robustness in translation?revolving and proportion transforms. The results show that this approach has better performances not only in robustness, but also in watermark- invisibility. Thus, this way avoids unlawful second-hand exploitation or application availably.

9060-57

Multiple watermark algorithm on fighter's 3D model based on DCT transform

Qi Hu, Jilin Business and Technology College (China) and Changchun Univ. of Science and Technology (China); Lang Zhai, Jilin Business and Technology College (China)

With the continuous application of battlefield simulation in military field, people get to focus on the issue that how to protect the 3D models' originality and security of weaponries effectively. This paper takes fighter's 3D model as an example, and adopts digital watermark technique to embed the copyright information into it. And propose a multiple watermark plan on 3D mesh model based on DCT transform. Firstly, put 3D model to affined transform, and consider the center of gravity of 3D model as the base point of three-dimensional Cartesian coordinate, extract the vertex's coordinate data of 3D model after principal elements' analysis projected on three 2D planes of XOY?XOZ?YOZ. Take these three sets of two-dimensional discrete signal into DCT transform and embed two-dimensional digital watermark into three sets' middle-frequency coefficients after transform. Multiple watermark embedding achieves 3D model's robustness to simplification, noise and cut and so on under fixed-affine space. Experiments prove that this approach has not only strong robustness, but also fine watermark-invisibility. Thus, this way avoids unlawful second-hand exploitation or application availably.

9060-48

Lateral migration of particles in the Newtonian fluid

Masato Makino, Md. Hasnat Kabir, Jin Gong, Hidemitsu Furukawa, Yamagata Univ. (Japan)

Studying of lateral migration of particles has a long history in fluid mechanics. In the Stokes approximation, non-charged rigid spherical particle in dilute solution does not migrate to a direction perpendicular to external field. For example, the spherical particle is placed in the vicinity of the wall. The particle doesn't move when a flow field, which is parallel to the wall, is applied. However, the lateral migrations are observed in dispersions of non-spherical and deformable particles. In this study, the migrations of skewed particles, chiral particles, droplets and non-spherical rigid particles are examined by computer simulations.

The skewed particle has a translation-rotation coupling. When the skewed particle settles down, the orientation of the particle rotates in periodic motion like a top-spin. The trajectory of the skewed particle also has periodical.

The chiral particle cannot be superposed on its mirror image, which is like our right and left hands. The chiral particle under simple shear flow moves to the flow direction and perpendicular to the flow as a secondary effect. The direction of the perpendicular motion depends on the particle's chirality. Our simulation is applicable to a separation tool for racemic mixture of chiral particles.

The interaction among particles causes a segregation of some kind of particles. For example, a dispersion of large and small droplets is concerned. The large droplets in a channel migrate to the center of the channel. On the other hand, small ones move to the vicinity of the wall.

9060-50

Experimental and numerical study of cellulose-based electro-active paper energy harvester *(Invited Paper)*

Zafar Abas, Heung Soo Kim, Dongguk Univ. (Korea, Republic of); Lindong Zhai, Jaehwan Kim, Inha Univ. (Korea, Republic of)

In this present study experimental and finite element analysis of cellulose based electro-active paper energy harvester is presented. Electro-active paper coated with metal electrode is a smart form of cellulose and exhibit piezoelectric effect. Specimens were prepared by depositing electrodes on both sides of the cellulose film. A 50x50 mm cellulose film coated with aluminum electrodes was bonded on 300x50x1 mm aluminum cantilever beam. The thickness of cellulose film was 20~30 μm. The output response from EAPap was recorded by conventional energy harvesting experimental setup at the fundamental natural frequency of the EAPap cantilever beam. The first natural frequency of EAPap bender was 5.1 Hz. A coupled field finite element model is developed to validate the experimental results. Frequency response analysis and transient analysis is performed on the based excited aluminum cantilever beam deposited with EAPap patch. A comparison of voltage generated on the electrode surface by experimental setup and numerical model will be presented. The response of electro-active paper at different input acceleration amplitude will also be studied. This will help to compare the response of electro-active paper at particular frequency and acceleration amplitude in line with the ambient vibration sources. Even though the electro-mechanical coupling coefficient of electro-active paper is lower than other available piezoelectric materials, it is biocompatible and naturally occurring polymeric material. It is also very flexible and posses similar piezoelectric characteristics such a PVDF which inspire to use EAPap in energy harvesting applications.

9060-51

Composite of polydiphenylamine/zeolite Y as sensing materials for halogenated solvents

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(Thailand)

Polydiphenylamine and zeolite Y composite were fabricated and tested for the ability to detect the halogenated solvent vapors; dichloromethane, 1,2-dichloroethane, and chloroform. In order to improve the electrical conductivity selectivity of the composite zeolite Y was modified by the dealumination process. The structure and composition are investigated by Fourier transform spectroscopy and X-ray fluorescence spectrometer, respectively. The effects of acid treatment time of the dealumination process and the zeolite Y content are investigated. The sensitivity of the composites with the dealuminated zeolite Y exhibits a higher sensitivity value when exposed to the solvents relative to the pristine zeolite Y. The optimum acid treatment time which provides the highest sensitivity is 12 hr. The selectivity of the composites towards the halogenated solvents is in this order: dhiclоromethane > 1,2-dichloroethane > chloroform, respectively. The optimum dealuminated zeolite Y content in the composites is 30% v/v.

9060-53

Organic nanowire crystals from solution coating

Olaf Karthaus, Masahiro Kawahara, Chitose Institute of Science and Technology (Japan)

Charge Transfer (CT) Complexes can be formed between aromatic electron donor and acceptor molecules. The molecules usually stack face-to-face and form columnar structures of 1:1 (sometimes also 2:1) complexes. These complexes show a new red-shifted and broad absorption band, which is due to a new molecular orbital that is shared between the molecules. Some complexes also exhibit strong fluorescence. Thus the electronic states of both donor and acceptor are changed. This, and the packing of the molecules into columns make them interesting for electronic and photonic applications, such as OFETs, LEDs and solar cells. By combining various donor and acceptor compounds a wide variety of CT complexes can be formed.

Here, we report on the formation of long crystalline needles of such CT complexes that are formed by a self-organization process from solution on various substrates. We will also show how a library of various CT complexes can be formed on one single substrate, which is interesting for the screening of materials.

9060-54

Surface acoustic wave device for chemical and biological applications

Joo-Hyung Kim, Gwang-Hoon Kim, Inha Univ. (Korea, Republic of)

We investigate surface acoustic wave (SAW) sensor for chemical and biological detector as frequency control elements in oscillator circuits, which work on the principle of mass loading and are highly sensitive to minute quantities of chemical analyte loading on the SAW propagation path. Important features that define the performance of these sensors are selectivity, sensitivity, stability, response time and dynamic range. In this paper, two inter-digital transducers (IDT) for working frequency of 50MHz, 100 MHz were designed and fabricated using conventional lift-off technique. The shift in SAW velocity due to surface loading leads to a shift in phase, which in turn generates a shift in frequency of the oscillator is confirmed. By different concentration of chemical vapor, the sensitivity of SAW devices will be presented.

9060-55

Ultra-small ZnO: Cu nanoparticles by ultrasonic chemical route for sensing applications

Yogesh C. Goswami, U. P. S. Gahlaut, Vijay Kumar, ITM Univ. (India)

Ultra small ZnO:Cu nanoparticles were obtained by ultrasonic Chemical route. The precursor used in the synthesis is Zinc acetate mixed with Ethanol and Copper Chloride was used for doping. The mixture was magnetically stirred and heated to 60oC for 2-3 hrs to obtain homogeneous solution. The gel was obtained by keeping the solution for another 24 hours. The particles were obtained by centrifuge the gel. The obtained samples were characterized by Optical transmission and photoluminescence studies. The strong blue shift in the optical band gap of copper doped ZnO from 3.2 to 4.76 eV confirms the small size of particles. All the ZnO nanostructures also show strong band-edge photoluminescence. Undoped ZnO nanostructure exhibits a near-band-edge UV emission at 36n0 nm and a broad defect related blue emission at 440 nm. Addition of Copper improves the photoluminescence peak in UV region with an additional peak observed in middle UV Region at 230nm. Other emissions such as yellow green or blue have also been observed. The UV emissions of the samples are centered at 3.42–4.90 eV, which is higher than the energy band gap of bulk ZnO. This confirms the size of particles comparable to the Bohr radius of ZnO. The size of the particles estimated using position of green band show that on increasing the Cu doping, the size decreases from to 23 nm to 3.4 nm which make him suitable for UV applications

9060-58

Powering nanorobotic devices: challenges and future strategies

Krishna Moorthi Sankar, Accendere KMS Labs. (India)

Nanobots require much different energy sources than usual robots as they are too small for the typical energy sources for a robot like batteries, solar cells or air-pressure cylinders. Their energy sources should not be the ones that need constant replacements and adjustments as nanobots will usually be situated in places like the interior of a human body where they cannot be constantly amended or physically handled. Powering nanobots is a critical challenge as the energy sources for a nanobot are still developing and are very costly and, in the case of most energy sources, polluting.

Traditionally, most robots have a solar cell or some kind of battery pack, but obviously these are too large for nanobots. Here, the answer may lie in nuclear technology. Researchers consider it highly likely that when equipped with a thin film of radioactive material such as radium, francium etc., nanobots will be able to fuel themselves on particles released by decaying atoms. This fuel technology is easily scaled down to nano-size. It also proves immensely efficient because with such a self-driven system in place, nanobots would be able to function indefinitely. They would never require a replacement fuel cell as their required energy is much lower than what the radioactive material can provide and it will take more than a century before the nanobots run out of energy. There is a school of thought that this radioactive film coated with protective polymers can prevent leakage of harmful and toxic materials into the human body. But polymers that can protect against radioactive decay are yet to be developed.

A highly developed and sophisticated version of acquiring nuclear energy to power nanobots is called Optoelectric Nuclear Battery. An Optoelectric Nuclear Battery is a device that converts nuclear energy into light, which it then uses to generate electrical energy. Usually, a beta-decay undergoing isotope is suspended in a fluid containing luminescent (glowing on passage of ionizing radiation like beta particles) excimer gas molecules. This permits a nearly lossless emission of beta electrons from

the isotope. The electrons then excite the Heterodimeric diatomic gases (complexes involving a noble gas and a halide) such as xenon chloride whose excimer line is selected for the conversion of the radioactivity into a surrounding photovoltaic layer such that a lightweight, low-pressure, high-efficiency battery can be made. This battery can be attached to nanobot giving it more power and efficiency to last for a very long time without needing replacements. [1]

Another safer way to provide energy to nanobots would be the traditional way – solar cells (batteries that use photons to provide energy by converting light energy into electrical energy or photons into electrons). A Quantum Dot is a crystalline nanoparticle made up of semiconductor materials that confines the motion of conduction band electrons, valence band holes, or excitons (bound state of an electron and electron hole attached to each other) in all three special dimensions. It is small enough to display quantum mechanical properties. Quantum Dot Solar Cells are nanoscale solar cells that use quantum dots as absorbing photovoltaic material instead of commonly used materials such as silicon. The addition to quantum dots to solar cells could lead to a tripling in efficiency, boosting from the usual 10% to 40% or 60%. Quantum dots are able to extract two or three electrons for each incoming photon which is an unprecedented feat. The amount of energy produced by a quantum dot solar cell varies with the colour and nature of the material of the quantum dot used and the number and efficiency of quantum dots used. But generally, a single Quantum Dot Solar Cell can provide the energy needed for nanobot to work at any instant provided there is a constant source of light. Nanobots inside the human body can be provided with harmless light radiation which can power the robots. Light for these solar cells can also be provided using the Optoelectric Nuclear Battery and a beta-emitter isotope.

According to the scientists at Cornell University, Nanobots could be powered by the same chain of chemical reactions that propel sperm toward an egg. The researchers are trying to reproduce the steps whereby a sperm's whip-like tail generates energy using the mitochondria in its midsection. Running the length of the tail of the sperm is a fibrous sheath with 10 enzymes attached to it. These enzymes act in series to break down glucose into ATP, the energy source for cells, in a process known as glycolysis. The researchers have currently managed to attach three of the 10 enzymes to a computer chip and confirm that the enzymes still work. If they can attach all 10 enzymes, they'll have a working version of a sperm engine, which could then be attached to nano-devices. This is an effective method to provide energy to a nanobot as the energy produced in moving a single sperm will be enough to power a nanobot for a long period of time.[2]

Another possible way to power the nanobots would the same method by which hydroelectricity is made. Nanobots travelling in the blood vessels with a relative velocity not equal to zero could have a rotating generator attached to their surface. These generators could be rotated by the kinetic energy of the flowing blood and thus the nanobot could be powered. Though the velocity of flow of blood is very slow ranging from 0.03 cm/s in the capillaries to 40 cm/s in aorta, the energy requirements of nanobots is equally small. The kinetic energy from the flow of blood in blood vessels can power nanobots as efficiently as most other options can. If the energy converted from the blood flow in the aorta where kinetic energy of blood is high can be stored, the nanobots can also be sent to lymph and tissues where there is no running blood.

This paper discusses the aforementioned and other techniques of powering devices in the nanometer regime, highlighting challenges associated with the same and strategies to overcome the same.

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9060-60

ZnO-CdS nanowire arrays with composite nano films for optical absorption

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Nanowire arrays have demonstrated unusual optical absorption property in solar cell application. We study a new microstructure design of nanowire arrays in conjunction with nano films composite for a strong light trapping at a wide range of frequency. Numerical and analytical analysis of the optical absorption in the composite thin film will be conducted to show its potential applications in solar cells. The microstructure effects of wire diameter, length, and filling ratio on the absorptance of nanowire arrays will be simulated. The study reveals that nanowire arrays with proper filling ratio could have much lower reflectance compared to thin films. In a high-frequency regime, nanowire arrays have higher absorptance than their thin film counterparts.

9060-14

Pericardial effusion ("dancing heart") monitoring by vector cardiograph

Prashanth S. Kumar, Univ. of Arkansas (United States); Vijay K. Varadan, Univ. of Arkansas (United States) and The Pennsylvania State Univ. (United States)

No Abstract Available

9060-31

Printing nanotube/nanowire for flexible microsystems *(Keynote Presentation)*

Jin-Woo Choi, Ryan P. Tortorich, Louisiana State Univ. (United States)

Printing becomes an emerging manufacturing technology for mechanics, electronics, and consumer products. Nanotubes and nanowires have recently been used as materials for sensors and electrodes due to their unique electrical and mechanical properties. Printed electrodes and conductive traces particularly offer versatility of fabricating low-cost, disposable, and flexible electrical devices and microsystems. While screen-printing has been a conventional method for printing conductive traces and electrodes, inkjet-printing recently attracts a wide attention due to its unique advantages including no template requirement, rapid printing at low cost, on-demand printing capability, and precise control of the printed material. Computer generated conductive trace or electrode patterns can simply be printed on a thin film substrate with proper conductive ink. However, for inkjet-printing of nanotubes and nanowires to form conductive traces and electrodes, there are few challenges that need to be addressed. One is nanotube/nanowire dispersion in an ink base solution while others include adjusting surface tension and controlling viscosity of the ink and treating the surface of the printing substrate. This work presents nanotube/nanowire ink preparation and its printing technique. A few examples of printed and flexible microsystems will be demonstrated and relevant issues will be discussed.

9060-33

3D printing of soft and wet systems benefit from hard-to-soft transition of transparent shape memory gels

Hidemitsu Furukawa, Jin Gong, Masato Makino, Md. Hasnat Kabir, Yamagata Univ. (Japan)

Hydrogels have high flexibility, extremely low frictional properties, substance permeability and biocompatibility by virtue of their high water content. However common hydrogels are too brittle to be used as industrial materials. In the last decade, several high-strength tough gels have been developed to overcome their brittleness. Recently we also successfully developed novel transparent shape memory gels (SMG) with high ductility via inter-crosslinking network (ICN), named ICN-SMG. The SMG memorize their original shapes during the gelation process. In the room temperature, the SMG are elastic and show plasticity (yielding) under deformation. However when heated above about 50°C, the SMG induce hard-to-soft transition and go back to their original shapes automatically. We focus on new soft and wet systems made of the SMG and try the 3-D printing of the SMG to fabricate novel smart soft and wet systems with more intricate shapes via computer-aided design and simulation. We make a SMG medical bandage to cover and fix injured part easily. Also we make a SMG optical varifocal lens. Further we develop eyeball robot by applying the SMG. These actual applications prove the SMG will be conveniently used to make soft robots. Additionally, now we are trying the 3-D printing of the SMG to fabricate novel smart soft and wet systems with more intricate shapes via computer-aided design and simulation.

9060-34

Material characterizations and electrical transport in Sn-, Se-, and Te-based binary/ternary semiconductors alloys and Schottky diodes

Naresh Padha, Univ. of Jammu (India); Ajit Khosla, Concordia Univ. (Canada)

Sn and Se based binary and ternary compound semiconductors have demonstrated applications in different areas such as infrared optoelectronic, switching devices, solar cells and other solid state electronic devices. Shortfall of one particular material is overcome by changing its structure or material. A brief review of changing characteristics of Sn and Se based thin films as well as schottky devices were studied on changing the structure or compositions of undertaken materials e.g. emergence of SnSe2 is due to its change in structure and SnSeTe due to change in composition while SnSe2Te is due to change in structure as well as composition. The films have been deposited on changing substrate temperature as well as film thicknesses. Thin films thus obtained have been investigated on the basis of their structural, morphological, electrical and optical properties. The films have been used for their schottky diode formation which subsequently studied for the temperature dependent C-V and I-V behaviour. While SnSe and SnSeTe were observed to be p-type Orthorhombic with preferred orientation along <111> and <121> planes, those of SnSe2 and SnSe2Te are n-type hexagonal and oriented along <101> and <001> planes respectively. Their grain size varied from 15.30 nm (SnSe2Te) to 37.25 nm (SnSe2); resistivity varied from 91 ohm-cm (SnSeTe) to 150 ohm-cm (SnSe2) and bandgap from 1.67eV(SnSe2) to 0.8eV (SnSeTe). The room temperature I-V characteristics of the schottky diodes formed from these films indicated ideality factor varying 1.87 (SnSeTe) to 1.26(SnSe2); barrier heights from 0.59eV (SnSeTe) to 0.75eV (SnSe2) and breakdown voltage from 1.15V (SnSe2) to 1.57V (SnSe2Te). The temperature dependent I-V and C-V characteristics indicated ideality factor decreasing and barrier height increasing with increase in temperature. The temperature dependence has been explained on the basis of 'barrier inhomogenities' existing over the MS interface with mean barrier height varying from 0.94eV (SnSeTe) to 1.27eV (SnSe2) with respective standard deviations of 14% (SnSeTe) and 17% (SnSe2). Further, the breakdown voltages has been seen increasing with decrease in temperature and thus provides negative temperature coefficient and demonstrate soft breakdown which indicated 'Defect Assisting Tunneling' existing in the undertaken schottky diodes. Further, there have been some variations between the experimental data vis-a-vis that generated on the basis of GD of BHs which indicated the possibility of tunneling current component in the current transport phenomenon of Schottky Ddiodes.

9060-35

CuIn0.81Al0.19Se2 materials and Schottky diodes for solar cell application *(Invited Paper)*

Naresh Padha, Univ. of Jammu (India); Chetan J. Panchal, The Maharaja Sayajirao Univ. of Baroda (India); Usha Parihar, Univ. of Jammu (India); Ajit Khosla, Concordia Univ. (Canada)

Al/p-CuInAlSe2 Schottky Diodes were fabricated under the optimized conditions of substrate temperature and film thickness. The parameters of the undertaken diodes such as ideality factor (?), barrier height (?bo) and series resistance (Rs) were calculated from the downward curvature of the current-voltage characteristics. The reverse characteristics of the undertaken schottky diodes showed a non-saturating behaviour indicating the spatial inhomogeneity of barrier heights. These diodes were undertaken for their temperature dependent current-voltage (I-V) as well as capacitance-voltage (C-V) analysis. The parameters extracted out of these were found to be strongly temperature dependent; wherein, ?bo increased, while ? and Rs decreased with increasing temperature. The temperature dependent behaviour of these diodes depicted 'barrier inhomogenities' over the undertaken diode area and analyzed to be due to several parallel diodes each comprising of individual barrier heights and ideality factors. This temperature dependence of the current voltage behaviour has been governed by the Gaussian Distribution of barrier heights spread over the entire diode area and the extent of inhomogeneity has been found of the order of 15%. The conventional Richardson plot showed non-linear behaviour which on the inclusion of current contribution due to inhomogeneity factors provided effective Richardson values closer to the reported ones (= 30A/cm2K2) thus, confirming the Gaussian Distribution of barrier heights. The discrepancy between barrier heights obtained from I-V and C-V measurements has also been interpreted. The undertaken Al/p-CuInAlSe2 Schottky Diodes parameters when compared with Al/p-CuInSe2 ones demonstrated improved values i.e. decreased ? as well as Rs and increased ?bo values. Moreover, CIAS thin films possessed increased bandgap and absorption coefficient values when compared with CIS thin films. Due to this increase in absorption coefficient and shift in frequency values (because of change in Eg value), enhances the scope of the undertaken CIAS material for its solar cell device applications.

9060-36

Dielectric relaxation in Sr(Co1/3Nb2/3)O3 compound: a candidate for microwave applications *(Invited Paper)*

Chetan J. Panchal, P. K. Mehta, The Maharaja Sayajirao Univ. of Baroda (India)

Relaxor ferroelectric compounds Sr(B1/3Nb2/3)O3, where (B = Mg2+, Co2+, Cu2+), synthesized by standard solid state reaction technique, exhibit strong correlation between structure, dielectric and transport behavior. The structure changes from highly distorted monoclinic structure in Mg and Co substituted samples to partially distorted Tetragonal structure in Cu substituted samples. In Cu based system significant Jahn- Teller distortion induced enhancements in dielectric properties have also been observed. Further, weak Jahn- Teller distortion

due to unevenly occupied t2g levels in Co2+ produces intermediate rise in ? as well as inbuilt flexibility to conduction electron movement enhances dielectric loss (tan?). On the other hand, strong Jahn-Teller effects in Cu2+ substituted compound, due to unevenly occupied eg levels, results in large enhancement in ? and frequency exponent 's' (>500 at 300K temperature & at 10KHz frequency) . At the same time, sample shows significant fall in dielectric loss (<0.5) even at elevated temperatures (<450K) due to the localization of conduction electrons within oxygen octahedron. The UV-Vis studies give the wide energy band gap semi conducting values {Eg ≥3.00 eV}. The improved physical properties of Sr(Cu1/3Nb2/3)O3 compound makes it suitable for energy storage devices as well as microwave device applications at wide frequency range.

9060-37

Flexible printable electronics and sensors in engineering and medicine

Vijay K. Varadan, Univ. of Arkansas (United States)

Advances in smart sensors, miniaturization, and related technologies are prerequisites to the construction of a smart sensory system that can be used for applications ranging from health monitoring, electronic nose, to smart fabric. Low manufacturing cost, light weight, portability and flexibility are among the requirements for the smart sensory system in conjunction with wireless technology. Organic semiconductor technology has recently been envisioned to meet these requirements, and to encourage the development of organic semiconductor based sensors because of its low process temperature and potential for very low cost manufacturing.

9060-38

Principle and applications of micro-spectrometers *(Keynote Presentation)*

Yeonjoon Park, National Institute of Aerospace (United States); Sang H. Choi, NASA Langley Research Ctr. (United States); Hargsoon Yoon, Norfolk State Univ. (United States); Uhn Lee M.D., Gachon Univ. Gil Medical Ctr. (Korea, Republic of)

After some history of the development of spectrometers is reviewed, we compare the different forms of diffraction equations that can be used to construct conventional Fraunhofer and novel Fresnel spectrometers. We conclude that the miniaturization of each type of spectrometer is limited by the validity of approximations to the founding Huygens principle. Once a new approximation form is established for smaller dimensions, miniaturization of spectrometers beyond today's limit can be accomplished. A new high-dynamic-range Fresnel micro-spectrometer in a tiny chip package will be demonstrated. Numerous applications of micro-spectrometer chips for the medical field, home electronics, nondestructive evaluation in the aerospace industry, and the chemical industry will be suggested.

9060-39

Cellulose-based soft gel like actuator for reconfigurable lens array *(Invited Paper)*

Kishore Kumar, Inha Univ (Korea, Republic of); Mithilesh Yadav, Xiaoyuan Gao, Inha Univ. (Korea, Republic of); Seongcheol Mun, Inha Univ (Korea, Republic of); Jaehwan Kim, Inha Univ. (Korea, Republic of)

Cellulose hydrogel can be made from a cellulose solution through physical cross-linking. Because cellulose has many hydroxyl groups which can form hydrogen bonding linked network easily. To dissolve cellulose, N-methylmorpholine-N-oxide (NMMO), ionic liquids (ILs), LiCl/dimethylacetamide (DMAc) solvent systems will be used. Also blending with polyvinyl alcohol (PVA) will be attempted to improve its electro-active behavior of cellulose based hydrogel. The synthesized gel will be tested for electro-active behavior in terms of strain, electric field strength, response time, repeatability, durability as well as for physical properties in terms of Young's modulus, transparency and dielectric constant. This cellulose based gel can be used for reconfigurable lens array.

9060-40

Transparent and flexible haptic array actuator made with cellulose acetate for tactile sensation

Md. Mohiuddin, Hyun-Chan Kim, Inha Univ. (Korea, Republic of); Sang-Yeon Kim, Korea Univ. of Technology and Education (Korea, Republic of); Jaehwan Kim, Inha Univ. (Korea, Republic of)

This paper reports an array type film haptic actuator based on cellulose acetate. Suggested actuator can vibrate with faster response time and various frequencies to give a range of haptic feedbacks to users which can be used in touch screen devices. Fabrication process, performance evaluation and electrostatic behaviour of haptic actuator are reported for tactile sensation. Cellulose acetate film is suitable for haptic actuator for its transparency, flexibility and high dielectric constant. An element of haptic actuator is made by using cellulose acetate film with patterned pillar, then haptic actuator elements arrayed to 3 x 3 to embed in haptic devices. Experiment to measure vibration acceleration is carried out on wide range of actuation frequency and voltage for single actuator to evaluate 3x3 array actuator. An equivalent finite element analysis also performed to compare the analysis results with experiments.

9060-41

PZT-actuated, 2D optical scanning image acquisition *(Invited Paper)*

Wei-Chih Wang, Univ. of Washington (United States)

Current endoscopes use either a bundle of optical fibers (optical waveguides) and/or one or more cameras having an array of detectors to capture an image. Thus, the diameter of these devices employed for remote imaging cannot be reduced to smaller than the image size. Even if one ignores additional optical fibers used for illumination of a region of interest (ROI), the scope diameter is therefore limited by the individual pixel size of a camera or by the diameter of optical fibers used to acquire the image. Therefore, it is apparent to achieve scopes with less than 3 mm overall diameter using current technologies, resolution and/or FOV must be sacrificed by having fewer pixel elements. All commercially available scopes suffer from this fundamental tradeoff between high image quality and small size. In this talk, we will present a minimally invasive medical imaging acquisition device using a small 2D optical scanner. The current 2D scanning image acquisition system utilizes a hybrid design of a microfabricated cantilever waveguide, a long slender rib shape SU-8 waveguide cantilever (length = 1mm, cross-section: Slab= 20 ?m ? 2 ?m, ridge= 5 ?m ? 2 ?m), and a small off-the-shelf 2D piezoelectric bimorph actuators (300 ?m x 1mm x 10cm) operating at resonant frequencies of 70 and 2800 Hz respectively, to generate a 40 lines resolution image. The image is acquired by a nearby photodetector based on the reflected intensity generated by the scanner. The current system is operated at + 18V AC input with 64.5 ?m vertical and 7.6 ?m horizontal tip displacement. Initial 1D image acquisition shows the system is capable of resolving a line pattern of 85 ?m with a gap space of 100?m with a S/N ratio of 10 dB. Due to inherent process imperfection and tooling in fabrication, the actual transmission efficiency is measured at 10%.

9060-42

Development of electrical impedance tomography for microwave ablation *(Invited Paper)*

Alistair L. McEwan, The Univ. of Sydney (Australia); Hun Wi, Kyung Hee Univ. (Korea, Republic of); Doan Trang Nguyen, Peter Jones, The Univ. of New South Wales (Australia); Vincent Lam, Wayne Hawthorne, Michael Anthony Barry, Westmead Hospital (Australia); Tong In Oh, Kyung Hee Univ. (Korea, Republic of)

Microwave ablation is attractive for the treatment of liver tumours as it provides rapid generation of large areas of heating without the requirement of the return electrode in radiofrequency ablation. In this study we assess the feasibility of electrical impedance tomography (EIT) to track the temperature changes during ablation in a gel phantom and porcine model. The time course and ablation areas compared well with EIT. EIT is more convenient and lower cost than other temperature monitoring methods such as MRI but spatial resolution is constrained by the relatively low number of independent measurements and ill posed reconstruction problem.

9060-43

Parylene-C passivation and effects on rectennas' wireless power transfer performance

Kyo D. Song, Camille Cooper, Keisharra Eldridge, Darryl W. Scott, Min H. Kim, Hargsoon Yoon, Norfolk State Univ. (United States); Jaehwan Kim, Inha Univ. (Korea, Republic of)

In this study, the effect of Parylene-C coated as a passivation layer on various rectennas is investigated in terms of their wireless power transfer performance. A passivation has been used for protection of rectenna circuits and their packaging in order for protection of the circuit elements and electrical insulation. Especially, wireless power receiving rectennas attached on sensors or on moving vehicles such as airship needs proper protection while they are exposed to harsh environment. In this research, a layer of Parylene-C thin film is used for passivation on rectennas and electromagnetic coupling by the coating is assessed by the measurement of receiving power levels. In this presentation, an electrochemical analysis method will also be introduced to measure the degree of water protection by a Parylene-C layer.

9060-44

Efficient RF energy harvesting by using a fractal structured rectenna system

Sechang Oh, Mouli Ramasamy, Vijay K. Varadan, Univ. of Arkansas (United States)

A rectenna system delivers, collects, and converts RF energy into direct current to power the electronic devices or recharge batteries. It consists of an antenna for receiving RF power, an input filter for processing energy and impedance matching, a rectifier, an output filter, and a load resistor. However, the conventional rectenna systems have drawback in terms of power generation, as the single resonant frequency of an antenna can generate only low power compared to multiple resonant frequencies. A multi-band rectenna system is an optimal solution to generate more power. This paper proposes the design of a novel rectenna system, which involves developing a multi-band rectenna with a fractal structured antenna to facilitate an increase in energy harvesting from various sources like Wi-Fi, TV signals, mobile networks and other ambient sources, eliminating the limitation of a single band technique. The usage of fractal antennas effects certain prominent advantages in terms of size and multiple resonances. Even though, a fractal antenna incorporates multiple resonances, controlling the resonant frequencies is an important aspect to generate power from the various desired RF sources. Hence, this paper also describes the design parameters of the fractal antenna and the methods to control the multi-band frequency.

9060-45

3D scanning of internal structure in gel engineering materials with visual scanning microscopic light scattering

Yosuke Watanabe, Jin Gong, Masato Makino, Md. Hasnat Kabir, Hidemitsu Furukawa, Yamagata Univ. (Japan)

Gels have unique properties such as low frictional properties, permeability and biocompatibility due to their high water content. In the last decade, several high-strength gels promising for extending the application of gels as industrial materials have been developed. While these trials were done, the gels have been hardly used in the industrial fields. One of the major issues is difficulties in controlling the internal structure of gels caused by the frozen inhomogeneities. To solve this problem, the scanning microscopic light scattering (SMILS) has been originally developed. In this system, the resulting data provides the statistically-averaged distribution corresponding to the internal structure of gels, which are very important in characterizing physical properties of soft matters. In this study, firstly, we show the new system named Visual-SMILS that is assembled in order to investigate the inhomogeneity of gels in two-dimensional. The new apparatus differs from SMILS in that it use three laser sources, inverted microscope and the galvanometer mirror that can scan the laser in 2D field at fixed scattered angle. We try to provide the 2D density map of crosslinkingpoint in gels with Visual-SMILS. Secondarily, we propose the method of quantitative analysis derived from the internal structure and the physical properties of the gels. The crosslinking densities of gels are precisely examined experimentally with the SMILS and theoretically with the tensile test and the water content. By comparing the three quantities, we can guess the network of gel. Based on these points, we believe this system is to be applied to develop 3D gel-scanner.

9060-46

Yttrium oxide-based three-dimensional metamaterials for visible light cloaking

Pratyush Rai, Prashanth S. Kumar, Vijay K. Varadan, Univ. of Arkansas (United States); Paul B. Ruffin, U.S. Army Research, Development and Engineering Command (United States); Christina L Brantley, US Army RDECOM (United States) and US Army Research, Development and Engineering Command (United States); Eugene Edwards, U.S. Army Research, Development and Engineering Command (United States)

Metamaterial with negative refractive index is the key phenomenon behind the concept of a cloaking device to hide an object from light in visible spectrum. Metamaterials made of two and three dimensional lattices of periodically placed electromagnetic resonant cells can achieve absorption and propagation of incident electromagnetic radiation as confined electromagnetic fields confined to a waveguide as surface plasmon polaritons, which can be used for shielding an object from in-tune electromagnetic radiation. The periodicity and dimensions of resonant cavity determine the frequency, which are very small as compared to the wavelength of incident light. Till now the phenomena have been demonstrated only for lights in near infrared spectrum. Recent advancements in fabrication techniques have made it possible to fabricate array of three dimensional nanostructures with cross-sections as small as 25 nm that are required for negative refractive index for

wavelengths in visible light spectrum of 400-700 nm and for wider view angle. Two types of metamaterial designs, three dimensional concentric split ring and fishnet, are considered. Three dimensional structures consisted of metal-dielectric-metal stacks. The metal is gold and dielectric is yttrium oxide, other than conventional materials such as FR4 and Duroid. High ? dielectric and high refractive index as well as large crystal symmetry of Yttrium oxide has been investigated as encapsulating medium. Dependence of refractive index on wavelength and bandwidth of negative refractive index region are analyzed for application towards cloaking from light in visible spectrum.

9060-47

Studies of ZrO2 electrolyte thin film thickness on the all-solid-thin film electrochromic devices *(Invited Paper)*

Chetan J. Panchal, The Maharaja Sayajirao Univ. of Baroda (India); Keyur J Patel, Science and Humanities Department, BITS Education campus, (India); Mukesh S Desai, Prashant K Mehta, The M.S. University of Baroda (India); I Yu Protsenko, Sumy State University (Ukraine); Ajit Khosla, Concordia Univ. (Canada)

The Electrochromic device (ECD) controls the optical properties such as optical transmission, absorption, reflectance, and/or emittance in a continual but reversible manner on application of a voltage. This property enables the ECD to be used for numerous applications like smart-window, EC mirror, and EC display. The basic structure of solid-state thin film ECD consists of glass substrate / transparent conducting electrode (TCO) / ion-storage layer (IS) / solid-electrolyte / EC layer / TCO. In solid-state ECD the electrolyte is the most important layer for ion transport between EC layer and ion-storage layer. We have prepared an all-solid-thin film ECD structure in our laboratory consisting of layers ITO / NiO / ZrO2 / WO3 / ITO on a glass substrate. The device performance includes transmittance modulation and open circuit memory effect, which is affected by the thickness of the electrolyte used in the devices. In the present paper, the optimization condition of the ECD performance as a function of variations in the ZrO2 electrolyte thin film thickness is discussed. The indigenously developed devices' characteristics like optical modulation and memory effect with different ZrO2 thickness are also been presented. The transmittance modulation and memory effect improved with increase in the thickness of ZrO2 electrolyte. The device having 5000Å ZrO2 thickness shows good transmittance modulation (56 %) in the wavelength range of 450 - 1000 nm with open-circuit memory effect of 170 min.

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9061-1

Surface acoustic wave action on microfluidic channels and microparticles *(Keynote Presentation)*

Erin R. Dauson, Kelvin B. Gregory, David W. Greve, Irving J. Oppenheim, Carnegie Mellon Univ. (United States)

Standing surface acoustic waves generated on SAW devices, or plate-like waves when operating at lower frequencies, can move microparticles in a fluid suspension to nodes or antinodes. That behavior is of interest because transporting, concentrating, and separating microparticles (including bacteria) has scientific and industrial significance. In an earlier paper we described lithium niobate SAW devices operating near 20 MHz, aligning microparticles in microfluidic channels fabricated from polydimethylsiloxane (PDMS, silicone).

Most investigators have used soft lithography and PDMS casting to create branched microfluidic channels in experiments for particle concentration and separation. However, that practice carries constraints, including the absorption (damping) of most of the wave energy. We discuss our recent studies with polymethyl methacrylate (PMMA, acrylic), which is relatively rigid, using micromilling to create branched microfluidic channels.

We also present simulation results and experimental measurements for acoustic waves in two different SAW device designs, both fabricated on Y-cut Z-prop lithium niobate with 0.5-mm thickness. The feature size in one design yields a resonant frequency of 17.4 MHz, at which the wave structure is in transition between plate waves and surface waves, while the feature size in the second design yields a resonant frequency of 34.8 MHz, at which surface wave dominate. We discuss the implications of wave structure when reflecting waves from interdigitated transducers (IDTs) as they are commonly used in SAW devices. We show data characterizing the time required for particles to align, and then discuss our recent studies to sort microparticles by size.

9061-2

Smart design *(Keynote Presentation)*

Diann E. Brei, Univ. of Michigan (United States)

While technologies based upon smart materials hold many benefits for industry, it has been a long journey to transition these into real products. The field of smart materials and structures is viewed as “enabling” or “emerging” spanning either a) new markets where the products are first generation without a clear application and there is an absence of design models present so empirical developmental methods must be employed, or b) developing markets where there are a few guiding models/methods but the products are not optimized and not reaching their full commercial potential. Even though the fundamental science is present for many smart materials such as shape memory alloys or piezoelectrics, the technology and industrial infrastructure is limited. Specifically, there are little to no significant workable models, design tools, and engineering data related to material uniformity/reliability and the effect of environmental factors and use history on performance and use life. Most importantly, the workforce is unfamiliar with the field and how to incorporate and utilize (i.e. engineer in) the distinct responses of smart materials to provide competitive products with unique properties. There needs to be a clearer path to transition all the progress made during the past twenty years of research into fruitful commercial products, especially within high-volume, low-cost markets. Great strides have taken place to address these design and development issues for transition of smart material technology to production including 1) targeted material research necessary for productization, 2) design of disruptive technologies providing a commercial competitive edge, 3), supporting design methods and tools for faster transition into technology, and 4) education of the workforce. All of these are necessary for a successful business case. This talk will discuss these efforts from a technological design and development perspective with application examples from several industries such as General Motors and FDA fast track medical technologies. The importance of collaborative, synergistic relationships spanning from basic research to device design into system integration will be highlighted as crucial for successful transition from emerging smart material research of today to competitive commercial products of tomorrow.

9061-3a

One the use of EMI for the health monitoring of bonded elements

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The low weight, robustness and fatigue resistance of adhesive joints make them suitable for structural joints. A fully developed nondestructive evaluation techinque however is needed and various methods have been investigated to monitor and assess the quality of bonded joints. In the present paper the application of the electromechanical impedance (EMI) technique is proposed. In the EMI method a piezoelectric transducer (PZT) is attached to the structure of interest. The sensitivity of the PZT to the structure’s properties and low power consumption make the EMI method feasible for real time structural health monitoring.

In this study we investigated the sensitivity of a PZT to the curing and quality of the adhesive used for bonded joints. A PXI unit running under LabVIEW and an auxiliary circuit were employed to measure the electric impedance of a PZT glued to an aluminum plate. The system aimed at monitoring the bond line between an aluminum strip and the plate. The conductive signature of the PZT was measured and analyzed during the curing.

The experimental results show that the electromechanical impedance technique is sensitive to the curing time and variations are observed for adhesives of different quality.

9061-4a

Damage identification with PVDF in two-dimensional structures using Lamb waves

Marco Menzer, Technische Univ. Freiberg (Germany)

This abstract is focussed on investigations concerning the damage diagnosis of surface structures using lamb-waves. Based on finite element calculations the potential possibilities for the detection of delaminations, inclusions or cracks have been investigated. For the actuator and sensor material a thin PVDF foil has been used, which was applied to the corresponding component. The advantage of these foils over piezoceramics is that they are also applicable to arbitrarily curved surfaces. By the defined arrangements of the electrodes and the generated lamb-waves occurring defects can be identified. The exact localization becomes possible with the help of runtime calculations.

9061-5a

Metamaterials enhanced acoustic sensing

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Acoustic sensors play an important role in many areas, such as safety (e.g., sonar arrays), public health (e.g., ultrasonic imaging), surveillance (e.g., underwater communication and navigation), and industry (e.g., non-destructive damage detection). However, fundamental limitations in current sensor systems and functional materials hinder the development of acoustic sensing technology. In this paper, we present metamaterial based acoustic sensing systems that can overcome the pressure field detection limit and offer multiple functionalities. First, investigation into the fundamental physics of high-refractive-index acoustic metamaterials for sound propagation and amplification is carried out. To overcome wave impedance mismatch at the interfaces of acoustic materials, graded-index metamaterials are designed by gradually increasing the effective refractive index along the propagation axis. As a result, incident acoustic waves can be coupled into the metamaterial with a high efficiency. Furthermore, new acoustic sensing modalities based on a metamaterial-transducer hybrid system are experimentally demonstrated, which exhibit extraordinary pressure-field amplification and frequency multiplexing capabilities. This hybrid system employs high index metamaterials integrated with novel optical fiber probes to achieve remarkable acoustic sensing capabilities. The integrated photonic-acoustic system offers many advantages, including immunity to environmental perturbations, high sensitivity, high resolution, and low noise. An analytical model is derived to describe the acoustic wave dispersion and pressure field concentration in metamaterials, which has a good agreement with the numerical and experimental results. It is expected that the metamaterial enhanced acoustic sensing will lead to a technology breakthrough: acoustic sensors with unprecedented sensitivity and functionalities, which are highly desirable for many applications

9061-6a

A passively tunable acoustic metamaterial lens for damage detection applications

Hongfei Zhu, Fabio Semperlotti, Univ. of Notre Dame (United States)

The development of highly focused and directional excitation has always been a major area of research in SHM. To-date, Phased Array (PA) technologies have been among the most successful techniques to achieve ultrasonic beamforming for SHM applications. Nevertheless, these systems require a large number of transducers which is seen as a major downside from the SHM perspective because it results in increased probability of malfunction and false alarms. Also, the excitation produced by PA is not the result of a collimated ultrasonic beam while instead of wave superposition. From a SHM perspective, non-collimated waves are less suitable because increases the background noise due to boundary conditions induced back-scattering. In this paper, we present a novel approach to ultrasonic beam-forming and beam-steering in structures based on metamaterial inspired embedded acoustic lenses. The lens design exploits the concept of acoustic drop-channel where multiple waveguides are selectively activated by simply tuning the frequency of the excitation. The proposed design allows generating highly directional excitation by using a single ultrasonic transducer. First, the design and the performance of the lens are investigated numerically. Plane Wave Expansion and Finite Difference Time Domain methodologies are used to extract the dispersion characteristics of the metamaterial lens as well as to simulate the transient response of the lens embedded in a plate-like structure. The lens design is then experimentally validated on an aluminum plate where the lens is realized by through the thickness notches. The performances are estimated by reconstructing the dynamic displacement field via Laser Vibrometry.

9061-7a

Predicting damaged areas on a metal plate using electromechanical impedance technique with different frequency ranges

Sam Na, Kangjin Cho, Haeng-Ki Lee, KAIST (Korea, Republic of)

Conventional nondestructive evaluation (NDE) techniques such as acoustic emission, optical, thermograph, x-ray and other various techniques require expensive equipments and experts, often making it difficult for practical applications. On the other hand, the electromechanical impedance (EMI) method has been well known for this robustness and acceptable performance up to date. This method uses a single piezoelectric material to act as an actuator and a sensor simultaneously, making it suitable for structures with complex surfaces. However, this technique still has wide range of problems which needs to be investigated. For one, locating damaged areas on a host structure is known to be extremely difficult as this non-model based technique heavily relies on the variations in the impedance signatures. In this study, an attempt to locate the damaged areas on a metal plate is carried out by using various frequency ranges. Since increasing the frequency range decreases the sensing range and vice versa, one can possibly predict the damaged areas by altering the frequency range.

9061-8b

Real-time weigh-in-motion measurement using fiber Bragg grating sensors

Ying Huang, North Dakota State Univ. (United States)

Overloading truck loads have long been one of the key reasons for accelerating road damage, especially in rural regions where the design loads are expected to be small and in the cold regions where the wet-and-dry cycle places a significant role. To control the designed traffic loads and further guide the road design in future, periodical weight stations have been implemented for double check of the truck loads. The weight stations give chances for missing measurement of overloaded vehicles, slow down the traffic, and require additional labors. Infrastructure weight-in-motion sensors, on the other hand, keep consistent traffic flow and monitor all types of vehicles on roads. However, traditional electrical weight-in-motion sensors showed high electromagnetic interference (EMI), high dependence on environmental conditions such as moisture, and relatively short life cycle, which are unreliable for long-term weigh-in-motion measurements. Fiber Bragg grating (FBG) sensors, with unique advantages of compactness, immune to EMI and moisture, capability of quasi-distributed sensing, and long life cycle, will be a perfect candidate for long-term weigh-in-motion measurements. However, the FBG sensors also surfer from their frangible nature of glass materials for a good survive rate during sensor installation. In this study, the FBG based weight-in-motion sensors were packaged by fiber reinforced polymer (FRP) materials and further validated at MnROAD facility, Minnesota DOT (MnDOT). The design and layout of the FRP-FBG weight-in-motion sensors, their field test setup, data acquisition, and data analysis will be presented. Upon validation, the FRP-FBG sensors can be applied weigh-in-motion measurement to assistant road managements.

9061-9b

A participatory sensing approach to characterize ride quality

Raj Bridgelall, North Dakota State Univ. (United States)

Rough roads increase vehicle operation and road maintenance costs. Consequently, transportation agencies spend a significant portion of their budgets on ride-quality characterization to forecast maintenance needs.

The ubiquity of smartphones and social media, and the emergence of a connected vehicle environment present lucrative opportunities for cost-reduction and continuous, network-wide, ride-quality characterization. However, very few models exist that can transform inertial and position information from voluminous data flows into a consistent index of ride-quality, without requiring calibration of individual vehicle responses. This work introduces such a model – the Road Impact Factor. The model combines continuous data flows from connected vehicle sensors to produce an average value that is directly proportional to the International Roughness Index. The author will explain the theories developed, and the algorithm used to combine non-synchronized data streams from participatory sensors that sample their inertial and position output at different rates. The presentation includes a case study that characterizes and compares the roughness of a rail grade crossing relative to known adjacent smooth and rough road segments. This new capability will enable transportation agencies to continuously and cost-effectively monitor all rail grade crossings and other intersections with high fatality rates to understand the influence of ride-quality on traffic safety.

9061-10b

Impact event identification through real-time strain measurements

Mijia Yang, Saeed Ahmari, North Dakota State Univ. (United States)

The growing demand for real-time damage assessment necessitates development of an efficient inverse analysis algorithm with consideration of practical issues such as uncertainty in measurement. A mathematical model-based inverse analysis scheme is proposed to identify impact locations and reconstruct impact load time history of a simply supported plate through multiple levels of analysis. Proximity of the impact location is first determined by the triangulation method and the impact location is then refined by minimization of an objective function through the particle swarm optimization method (PSO). Loss of data due to filtration is addressed in further level by performing an interval analysis based on extreme measurement errors. The outcome of the analyses is a mean impact location, load time history, and a range of likely deviations. The extreme deviation in impact location is shown by bounding lines, which form a rectangle. The deviation in load time history is also shown by upper and lower bounding sinusoidal curves. The analyses results indicate that the proposed method can effectively locate the impact point and reconstruct the load time history even with the existence of noise in the measured response.

9061-11b

Performance of a movable flexible pipe-encapsulated FBG sensor developed for shape monitoring of multi-layered pavement structure

Huaping Wang, Wanqiu Liu, Zhi Zhou, Dalian Univ. of Technology (China)

The large span and heterogeneous components of multi-layered pavement structure usually bring about stochastic damage, and many modern approaches, such as ground penetrating radar, integral imaging and optical fiber sensing technology, have been employed to detect the degeneration mechanism. Restricted by the cost and universality, novel elements for pavement monitoring are in high demand. Optical fiber sensing technology for high sensitivity, long stability, anti-corrosion and resistance to water erosion then is considered. Therefore, a movable FBG sensor located in flexible pipe is developed, which has long stroke inside inner wall of the hollow pipe, and a full-scale shape of the structure could be sketched just with one FBG. A theoretical equation about the relationship between wavelength and coordinates has been provided, strain transfer mechanism has been taken into account for modify related error, and basic experiments have been fulfilled to prove its efficiency. Multi-layered pavement model embedded with this sensor will be accomplished to inspect its performance. The work in the paper will afford a feasible method for shape monitoring and would be potentially valuable for the maintenance and inverse design of pavement structure.

9061-12b

Strain and temperature distributions in concrete pavement panels under truck loads with Brillouin scattering measurement

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Thin concrete panels have recently been introduced to rapidly and cost-effectively improve the driving condition of existing roadways by laying down a fabric sheet on the roadways, casting a thin layer of concrete, and then cutting the layer into panels. This study is aimed at understanding the strain distribution and potential crack development of concrete panels under various truck loads in different seasons. Both laboratory and field tests on 6ft?6ft?3in concrete panels (full-scale) were conducted to understand the performance of concrete panels. To this end, six concrete panels were fabricated and tested in laboratory, replicating their field condition in application. Optical fiber sensors with Brillouin scattering technology were instrumented on the concrete panels and two panels in field implementation. The strain distributions as a fully-loaded truck moves across the instrumented panels are presented and compared with those from numerical simulations. The change in strain distribution in various seasons was investigated to understand the effects of temperature and freeze and thaw. In addition, the potential effect of the substrate movement on the performance of the concrete panels was also documented and analyzed.

9061-13a

ASR damage detection in concrete from ultrasonic methods

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Alkali-silica reaction (ASR) is a chemical reaction that can occur between alkaline components in cement paste and reactive forms of silica in susceptible aggregates when sufficient moisture is present. The ASR products, known as ASR gel, can cause expansion and cracking that damages the structure. We pass ultrasonic signals through concrete laboratory specimens and use the passband properties to detect the onset of ASR damage, or the presence of ASR damage while still at the microscale. We also report our studies of the influence of specimen size, moisture, and coupling conditions. Our test specimens are fabricated with aggregates known to be reactive and are then exposed to an aggressive environment to accelerate ASR development. We use swept-sine excitations and obtain pitch-catch records from specimens that have been exposed to the accelerated environment, along with control specimens that have been withheld from exposure. The passband distribution shows that high frequency components diminish with exposure, and correspond to the development of ASR damage at the microscale. The test results also show that the ultrasonic passband is logically related to specimen size. The ultrasonic passband technique has

also been tested under different moisture and coupling conditions, and the results indicate it to be robust to those condition changes.

9061-14a

Design and deployment of a prototype scour monitoring system

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This paper presents ongoing work on the development of a capability for 24/7 monitoring and detection of bridge scour. The paper includes a review of the design considerations that went into deployment of the first system, as well as an assessment of the performance of the first prototype. Scour is a leading cause of failure for bridges in the US, where nearly 60% of bridge failures are caused by hydraulic forces and nearly 24% of our nation's ~610,000 registered bridges are deemed structurally deficient or functionally obsolete. Scour occurs when moving water washes away sediment from around bridge foundations thus compromising the integrity of the structure. The scour sensing technology uses magnetic and magnetostrictive whisker-like sensors attached to posts buried in the soil around bridge foundations. As scour develops and the soil begins to erode, the sensors are able to detect water flow and automatically alert the bridge owner that remediation is needed.

The flow sensors used for this application have to perform in extremely challenging environments that can transition back and forth from being buried in sand, mud and rocks to being exposed to flowing/churning water that is carrying sand, mud and rocks. The flow sensors being used to perform reliably in these conditions are based on magnetic and magnetostrictive technologies. The magnetostrictive alloys evaluated for use in this application were iron-gallium and iron-aluminum, and were fabricated at the University of Maryland using patent pending rolling, annealing and texture development methods.

9061-15a

Data-driven finite element model estimation for built-up structures

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Data-driven subspace system identification techniques recently developed from the control theory provide a rich set of analytical tools for system identification of structural dynamics systems. Physical interpretation of black-box system identification models obtained from measurement data is direly needed to extract a physical description (i.e., discretized finite element model) of the target structural system. However, the physical interpretation of these black-box system identification models remains a major hurdle in their application to structural engineering problems such as structural health monitoring (SHM). In particular, little work has been done for built-up structures in the field. In this study, a novel experimental methodology of data-driven finite element models for built-up structures was presented with an inclusive solution for equipments and algorithms. The methodology utilized a reaction force actuator and a remote optic device, respectively, for practical actuation and a precision displacement measurement of built-up structures.

9061-16a

Structural health monitoring of unbonded posttensioning tendons by measuring relative strain variation in multi-strand anchorage

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Posttensioned segmental bridges are common throughout the US; however, in recent years, the incidence of tendon failure in bonded posttensioned bridges has raised questions regarding their design, construction, and maintenance. These failures have led to the investigation of the applicability of using replaceable unbonded tendons in segmental construction and new methods for monitoring their condition. This paper presents a novel approach to monitoring strand breakage in unbonded posttensioning tendons. In unbonded construction, the anchorage assembly usually undergoes severe stress-state condition as the entire prestressing force only passes through the deviator and end anchorage locations. The strain distributions in the anchorage mechanism, therefore, go through significant changes in response to the breakage of an individual wire or an entire strand in a multi-strand arrangement. In this way, breakage of a posttensioning strand can be identified by observing a non-uniform variation of the strain field over the anchorage region in contrast to a uniform variation of strains due to environmental or traffic loading. This paper outlines a framework of strand breakage detection based on the relative variation of strains in anchorage as a candidate health monitoring approach.
A reduced scale laboratory experiment is performed followed by an extensive finite element simulation to conduct a parametric study with wire/strand breakages at different locations on multi-strand anchorages commonly used in industry. Based on the observed strain variations from simulation, a statistical correlation model is proposed to determine optimum strain measurement locations to identify the damaged strand.

9061-17a

Scavenging vibration energy from seismically-isolated bridges using an electromagnetic harvester

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Long-span bridges are prone to wind or earthquake induced vibration. Tuned mass dampers (TMD's) are a common way to mitigate this excessive vibration of these structures. TMD's dissipate some energy input to the structures by changing their dynamic characteristics through conventional built-in dampers. In this study, it is proposed to investigate the feasibility of harvesting, instead of dissipating through heat, vibration energy by an advanced hybrid energy harvester. This control-hybrid energy harvester combines electromagnetic method (EM) with piezoelectric/magnetostrictive composite method (PM) to form an EM+PM system. It consists of an energy harvesting mechanical part and an energy harvesting power management part. To analyze the nonlinear behaviors of EM+PM system, this study will employ electromagnetic adaptive finite element analysis (FEA) to simulate electrical-output performances, such as the magnetic damping force and its alternating magnetic field. Next, a mathematical model for this harvester is developed and implemented on an ideal single-degree-of-freedom (SDOF) long-span bridge equipped with a TMD. The effect of this EM+PM harvester on the control performance of the TMD is analyzed and discussed. To validate, the applicability of the control-hybrid energy harvesting system for a long-span bridge, such as the Kap Shui Mun Bridge in Hong Kong, is also addressed.

9061-18a

Field testing of prototype systems for the non-destructive measurement of the neutral temperature of railroad tracks

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In both high speed and freight rail systems the modern construction method is Continuous Welded Rail (CWR). The purpose of the CWR method is to eliminate joints reducing the maintenance cost on the rail sections and car wheels. However the elimination of the joints increases the risk of rail breakage in cold weather and buckling in hot weather. In order to predict the temperature at which the rail will break or buckle it is critical to have knowledge of the temperature at which the rail is stress free; known has the Rail Neutral Temperature (Rail-NT). Through the licensing of the technology from the University of California, San Diego (UCSD) and under the sponsorship from the Federal Railroad Administration (FRA) Office of Research and Development, a field deployable prototype system has been developed in the laboratory and recently placed in the field for real world testing. The wayside Rail-NT prototype based on non-linear ultrasonic guided waves was been very successful in the laboratory and a blind field test. Based on these successes, in the summer of 2013 three prototype systems have been deployed to the Union Pacific (UP), Burlington Northern Santa Fe (BNSF), and AMTRAK railroads for further field testing and development. The results from these tests has given cause to take the current system, configured with off the shelf components, and develop a compact Original Equipment Manufacturer (OEM) system for possible use through the railroad industry. In this paper, the results of the field tests with the railroads in summer of 2013 are reported.

9061-19a

Visualized magnetic flux-based remote steel cable NDE system for steel cables in long span bridges

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A visualized magnetic flux based automated cable non-destructive evaluation (NDE) system was proposed that uses a magnetic flux leakage (MFL) sensor and a cable-climbing robot to monitor the steel cable in long span bridges. A wheel based Cable climbing robot was designed and fabricated to improve the accessibility to cable. And, a multi-channel MFL sensor head was fabricated and incorporated on the cable climbing robot. In addition, Wireless LAN communication was applied for remote data transmission and robot control. To verify the feasibility of the proposed cable inspection technique, a steel cable specimen with several types of damage was fabricated, and scanned by the fabricated cable NDE system to measure the magnetic flux density of the cable specimen. Measured magnetic flux signals were used to determine the locations and the levels of damage. Measured signals from the damaged specimen were compared with thresholds that were set for objective decision-making. In addition, the magnetic flux signal was visualized as a 3D MFL image for intuitive cable monitoring. Finally, visualized MFL image was compared with information on actual damages on specimen to confirm the accuracy and effectiveness of the proposed cable monitoring system. In addition, the field applicability of the integrated cable NDT system was verified through a field test at Seohae-bridge which is one of typical cable-stayed bridge in operation.

9061-20b

Enhanced vibration-based energy harvesting using embedded acoustic black holes

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In this paper, we investigate the use of dynamic structural tailoring to enhance the performance of piezoelectric based energy harvesting from operational vibrations of mechanical systems. In order to tailor the wave propagation characteristics of the host structure we exploit the concept of an Acoustic Black Hole (ABH). The ABH is an integral feature that can be embedded in the host structure allowing a smooth reduction of the phase velocity (virtually approaching zero) while minimizing the amplitude of reflected waves. The ABH thickness variation is typically designed according to power-law profiles of the type with . As a travelling wave enters the ABH, it is progressively slowed down and its wavelength is compressed therefore producing structural areas with high energy density that can be effectively exploited for energy harvesting.

After briefly reviewing the theory of the Acoustic Black Hole, this paper investigates its possible use to enhance the energy harvested using piezoelectric based devices. Fully coupled electromechanical models of an ABH tapered plate with surface mounted piezoelectric transducers (PZT) are developed. These models are used to numerically evaluate the performance of the ABH tailored structure under both steady state and transient excitation. The performances of the novel design are compared with the non-tailored structure in terms of instantaneous output voltage and Structural Intensity data. Results show that the tailored structural design allows a drastic increase in the harvested energy both for steady state and transient excitation. The effect of different design parameters is also investigated.

9061-21b

The effects of bonding layer on ultrasound generation and sensing using PWAS

Mazharul Islam, Haiying Huang, The Univ. of Texas at Arlington (United States)

This paper presents an analytical simulation model to study the effects of bonding layer on ultrasound pitch-catch signals generated and acquired using bonded PWAS transducers. The PWAS transducers are assumed to deform in longitudinal mode while both the longitudinal and flexural vibrations of the structure are considered to account for the multi-mode nature of ultrasound pitch-catch signals. The governing equations of the PWAS transducer under these two different structural vibration modes are derived by coupling the deformation of the PWAS transducers to the structural deformation through the shear deformation of the bonding layer. The governing differential equations were solved by implementing appropriate boundary and continuity conditions as well as adopting the reverberation matrix method (RMM). Parametric analysis is carried out to study how the unknown bonding layer parameters such as the shear modulus and shear reduction constant of bonding layer affects the ultrasound pitch-catch signals. The simulated pitch-catch signal will be matched with the experiment measurements by tuning the unknown bonding layer parameters.

9061-22b

Impedance-based damage identification enhanced via tunable piezoelectric circuitry

Jinki Kim, Kon-Well Wang, Univ. of Michigan (United States)

The piezoelectric impedance-based method for damage detection has

been explored extensively for its high sensitivity to small-sized damages with low-cost measurement circuit which enables remote damage monitoring. However, the amount of feasible impedance data is usually much less than the number of required system parameters to accurately identify the damage location/severity via an inverse formulation. This data incompleteness forms a highly underdetermined problem and because of this numerical ill-conditioning, the predicted damage parameters will be dramatically influenced by unavoidable measurement noise and the accuracy of the base-line model.

In this study, the state of the art of impedance-based damage identification is advanced by incorporating a tunable piezoelectric circuitry with the structure to enrich the impedance measurements. This piezoelectric circuitry introduces another degree of freedom to the structure and changes the dynamics of the coupled system. By tuning the inductance value, it is possible to perform various measurements under different system dynamics which reflects the damage effect. Therefore, if done systematically, notably increased sets of measurement can be obtained, which will improve the inverse problem to be less underdetermined. Clearly, we can expect the accuracy and robustness in damage identification to be significantly enhanced. Numerical case study on localizing damage in a fixed-fixed beam using spectral element method is performed to demonstrate the effectiveness of the new method for structural damage identification.

9061-23b

Generation and sensing of guided waves using in-plane shear piezoelectric wafers in metallic pipe

Wensong Zhou, Hui Li, Harbin Institute of Technology (China); Fuh-Gwo Yuan, North Carolina State University (United States)

Guided waves based techniques are effective and promising tools for the damage detection in pipes. The essential operations are generation and detection of guided waves in the objective structures utilizing the transducers. A novel in-plane shear (d36 type) piezoelectric wafer is proposed to generate and sense the guided wave, especially the torsional waves, in metallic pipes. For this wafer, in-plane shear deformation will occur when electrical field is applied along its z-direction. Moreover, compare to the conventional guided waves transducers, the proposed d36 type wafer, which is bonded on the surface of pipe, is able to generate not only the torsional waves but also the circumferential shear horizontal waves simultaneously with higher sensitivity in pipe. This paper presents the working mechanism of d36 wafer and results of finite element (FE) analysis mainly. Both displacement and voltage responses are obtained from pristine as well as damaged pipes, for which the notches with different direction and size are analyzed. Furthermore, reflection coefficients are employed to describe the severity of the damage. All results indicate this type of wafers has potential for simply providing quantitative information of damage in structural health monitoring of metallic pipes.

9061-24b

Structural design and analysis of an air vehicle smart fin embedded with single crystal piezoelectric actuator

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In order to substitute a conventional fin operated by hydraulic actuator, structural design and analysis of a smart fin embedded with single crystal composite piezoelectric actuator has been attempted in this paper. Sahin and Rabinovitch suggested and conducted study for a similar concept. The present air vehicle smart fin employed two unimorph actuators and two equally-spaced bimorph actuator within the cross-section. Skin of the airfoil was made of the general composite material, such as graphite epoxy. Finite element analysis software (MSC. Patran) and nonlinear contact analysis software (MSC. Marc) were used to analyze the present design. For simplified analysis for the present structural design, unimorphs were neglected for the moment. Then, piezoelectric actuators were replaced by aluminum sheet, and a uniform load toward the downward direction was applied on its trailing edge. Result showed small deflection in its magnitude but linear increase of it along the transverse downward direction. Further analytical results by realizing the piezoelectric material as actuators along with compatible control algorithm will be included in the final paper. The piezoelectric materials which will be presently applied include single crystal piezoelectric material PMN-29PT, and PI flim. The same analysis softwares (MSC. Patran, Marc) will also be used in that analysis. The present design and analysis will be extended to much further application such as the wing structure in the unmanned air vehicle and commercial aircraft.

9061-25b

Characterization of vibration transfer paths in nose gearboxes of an AH-64 Apache

AKM Anwarul Islam, Youngstown State Univ. (United States) and NASA Glenn Research Ctr. (United States); Paula J. Dempsey, NASA Glenn Research Ctr. (United States); Jason Feldman, Chris Larsen, Etegent Technologies, Ltd. (United States)

Health monitoring of rotorcraft components, which is currently being performed by Health and Usage Monitoring Systems (HUMS) through analyzing vibration signatures of dynamic mechanical components, is very important for their safe and economic operation. Vibration diagnostic algorithms in HUMS analyze vibration signatures associated with faults and quantify them as condition indicators (CI) to predict component behavior. Vibration transfer paths (VTP) play important roles in CI response and are characterized by frequency response functions (FRF) derived from vibration signatures of dynamic mechanical components of a helicopter. With an objective to investigate the difference in VTP of a component in a helicopter and test stand, and to relate that to the CI response, VTP measurements were recorded from 0–50 kHz under similar conditions in the left and right nose gearboxes (NGBs) of an AH-64 Apache and an isolated left NGB in a test stand at NASA Glenn Research Center. The test fixture enabled the application of measured torques – common during an actual operation. Commercial and lab piezo shakers, and an impact hammer were used in both systems to collect the vibration response using two types of commercially available accelerometers under various test conditions. The FRFs of both systems were found to be consistent, and certain real-world installation and maintenance issues, such as sensor alignments, locations and installation torques, had minimal effect on the VTP. However, gear vibration transfer path dynamics appeared to be somewhat dependent on presence of oil, and the lightly-damped ring gear produced sharp and closer transfer path resonances.

9061-26b

Structural damage detection using PZT sensors based on wavelet packet analysis and cross correlation function

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A structural damage detective method, which uses PZT sensors in vibration test, is proposed based on wavelet package analysis and cross correlation function. The damage detective method based on cross correlation function can only be effective in the condition that the

excitation signal is in a special frequency range. Aiming at expanding the application scope of the method, the signals from PZT sensors are processed by wavelet package analysis and the single reconstructed signals are acquired firstly.

Then the damage index is defined by the difference of cross correlation function amplitude between single reconstructed signals from PZT sensors in health and damage condition. The method only needs the vibration responses of PZT sensors in both health and damage conditions and the signal with any frequency range such as impact signal and white noise can be adopted as excitation signal. A numerical example of shear frame structure, in which the impact load and white noise are used as excitations, is conducted to demonstrate the advantage of proposed method compared with the one based cross correlation function purely. In addition, the feasibility and effectiveness of the method is also confirmed by a damage detection experiment of RC structure during seismic damage. It is shown that the proposed structural damage detective method can monitor and locate the damage accurately.

9061-27b

Non-contact damage detection of structure with oscillation using electromagnetic impedance sensing

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Magnetic transducers have been applied in impedance-based damage detection recently. Owing to the magneto-mechanical coupling characteristics between a magnetic transducer and the underneath metallic structure, a magnetic transducer can excite the host structure by means of the Lorenz force, and its electrical impedance is directly related to the host structure's mechanical impedance. . Therefore, the change of electrical impedance before and after damage occurrence can be used as damage indicator. Since there is no direct contact between the magnetic transducer and the host structure, it appears that the magnetic transducer has advantage in online health monitoring of many structures with complex geometries and boundaries. However, one key issue is that the coupling between the magnetic transducer and the host structure is strongly influenced by the lift-off distance (i.e. the distance from the transducer to the host structure) which changes as the structure is inevitably subject to oscillation/movement due to environment disturbance. In this research, we propose a new detection algorithm that can explicitly take the lift-off distance change into consideration to facilitate efficient and robust decision making. This algorithm is incorporated into an enhanced magnetic sensor with circuitry integration of properly chosen capacitance, and it is identified that the algorithm can further improve the sensor performance. Comprehensive case studies are carried out to demonstrate the new algorithm and sensor development.

9061-28a

Health monitoring of offshore wind farm structures

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Structural health monitoring (SHM) is a well-explored research field for promoting public safety and economic infrastructure maintenance in the detection of damage and localization of above-ground civil structures. However, a recent study revealed the statistical data that most problematic and weak links of structural systems were substructures including piers, foundations, and underwater components, not the superstructures. Still, effective monitoring methods for the underwater components, which are considered as main sources of failure, are lacking. In this paper, the feasibility of underwater structural health monitoring framework will be developed including multi-scale measurement of structural behaviors and underwater uncertainties, system identification, damage detection, and lifetime assessment of underwater component of offshore wind farm structures. A hybrid sensing system combining wireless smart sensors and high sensitivity displacement and strain sensors will be employed for measurement, with point measurement of temperature and other environmental measurements. A series of laboratory-scale as well as full-scale measurements of underwater wind farm structures will be conducted to determine the uncertainty effects on comprehensive structural health monitoring and lifetime assessment. Modal analysis was conducted to find the dynamic characteristics and fed into subsequent damage assessment. For lifetime assessment, the strain-time history data at the critical members are used to determine the stress spectrum. This SHM method can reveal real time structural health condition of wind farm structures and help owners to make decisions.

9061-29a

Operational model updating of spinning finite element models for HAWT blades

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Structural health monitoring (SHM) relies on collection and interrogation of operational data from the monitored structure. To make this data meaningful, a means of understanding how damage sensitive data features relate to the physical condition of the structure is required. Model-drive SHM applications achieve this goal through model updating. This study proposed a novel approach for updating of aeroelastic turbine blade vibrational models for operational horizontal-axis wind turbines (HAWTs). The proposed approach updates estimates of modal properties for spinning HAWT blades intended for use in SHM an Load estimation of these structures. Spinning structures present additional challenges for model updating due to spinning effects, dependence of modal properties on rotational velocity, and gyroscopic effects that lead to complex mode shapes. A stochastic Eigensystem realization algorithm (ERA) is applied to operational turbine data to identify data-driven modal properties including frequencies and mode shapes. Model driven modal properties are derived through modal condensation of spinning finite element models with variable physical parameters. Complex modes are converted into equivalent real modes through reduction transformation. Model updating is achieved through use of an adaptive simulating annealing search process to find the physical parameters that best match the experimentally derived data.

9061-30b

Nonlinear damage identification of breathing cracks in Truss system

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The breathing cracks in truss system are detected by Frequency Response Function (FRF) based damage identification method. This method utilizes damage-induced changes of frequency response functions to estimate the severity and location of structural damage. This approach enables the possibility of arbitrary interrogation frequency and multiple inputs/outputs which greatly enrich the dataset for damage identification. The dynamical model of truss system is built using the finite element method and the crack model is based on fracture mechanics. Since the crack is driven by tensional and compressive forces of truss member, only one damage parameter is needed to represent the stiffness reduction of each truss member. Assuming that the crack constantly breathes with the exciting frequency, the linear damage detection algorithm is developed in frequency/time domain using Least Square and Newton Raphson methods. Then, the dynamic

response of the truss system with breathing cracks is simulated in the time domain and meanwhile the crack breathing status for each member is determined by the feedback from real-time displacements of member's nodes. Harmonic Fourier Coefficients (HFCs) of dynamical response are computed by processing the data through convolution and moving average filters. Finally, the results show the effectiveness of linear damage detection algorithm in identifying the nonlinear breathing cracks using different combinations of HFCs and sensors.

9061-31b

Minimal mass design of tensegrity structures

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The focus of this research is to find ways to use minimal material to solve a structural design problem. Structural mass is greatly reduced if one can eliminate (at least statically) material bending. Tensegrity structures are mechanical trusses composed of compressive members (bars, struts, pipes) and tensile members (strings, tendons, cables) that are all axially loaded.

This paper provides a unified framework for minimal mass design of tensegrity systems of all tensegrity of any class (class k allows k bars to touch at their ends through any connections that act like frictionless ball joints). For any given configuration and any given set of external forces, we design force density (member force divided by length) and cross-section area to minimize the structural mass subject to an equilibrium condition and a maximum stress condition. The answer is provided by a linear program. Gravity forces can be treated. Stability is assured if we design a structure to have a positive definite stiffness matrix. We show that this condition is described by a linear matrix inequality. Hence the answer of the optimization problem with this stiffness constraint is provided by a convex optimization. Sometimes one must consider the behavior of the system under a variety of expected loads. This might cause a cable under tension in one load condition, while experience compression in another load condition. This paper also proposes a way to resolve this design issue. A numerical example produces a minimal mass structure for a cantilevered load.

9061-32a

Compressive strain sensing performance of RFID patch antenna sensors

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In this research, three designs of radiofrequency identification (RFID) antenna sensor are tested for compressive strain measurement. The first design is a passive (battery-free) folded patch antenna sensor with a planar dimension of 61mm ? 69mm. The second design is a slotted patch antenna sensor, whose dimension is reduced to 44mm ? 48mm by introducing slots on the top antenna layer to detour the surface current path. The third design is an active slotted patch antenna sensor that can draw power from a small-size solar cell to increase interrogation distance. A 3-point bending setup is fabricated to apply compression on a tapered aluminum specimen mounted with the antenna sensor. Extensive compression tests are conducted to verify the strain sensing performance of the three antenna sensors. Multiple compressive strain steps and interrogation distances are tested to investigate the strain sensing resolution of the antenna sensors. Experimental results show that the resonance frequency of the antenna sensor increases in an approximately linear relationship with respect to compressive strain. The compressive strain sensing performance, including strain sensitivity and determination coefficient, of the three RFID antenna sensors are calculated from the experimental data

9061-33a

Crack identification based on thin-film full-bridge strain sensors

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A sensing sheet based on large-area electronics consists of a dense array of discrete short-gauge sensor units, integrated circuits for collecting, analyzing and communicating data, and a flexible photovoltaic system that serves as both a power harvester and a protective layer. It is a promising structural health monitoring tool that can identify (detect and characterize) cracks in structures. Crack detection and characterization capabilities of the sensing sheet depend on the type of unit sensor and its sensitivity to the occurrence and opening of cracks. Full-bridge resistive strain sensors are capable of differential sensing, which significantly improves robustness against noisy signals from external sources and helps avoid large sinusoidal baseline signals that would affect the AC readout scheme applied to the sensing sheet. For this reason, we investigated the sensitivity of thin-film full-bridge strain sensors to cracks by conducting laboratory experiments in a temperature-controlled setting. The results showed a distribution of linear relationships with an average sensitivity of 0.0404 ?m/??. In addition, the effect of crack position and orientation with respect to the sensor was investigated, and both variables are shown to affect the sensitivity of strain sensors to cracks. The dispersion in linear relationships along with the effects of crack position and orientation led to the development of a probabilistic approach for crack characterization. In general, the results of this research show that full-bridge strain sensors can successfully detect and characterize cracks in structural materials and are therefore good candidates to utilize in a sensing sheet.

9061-34a

In situ phase change characterization of spray deposited PVDF thin films

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The development of a spray-deposited piezoelectric impact detection sensor is desired for aerospace, civil, and military applications, among others. Implementation of a poly(vinylidene fluoride) (PVDF)-based architectural coating is ideal for such a purpose as it is designed to be easily spray-deposited on complex geometries, be mechanically robust, and piezoelectric properties can be induced into the coating. In order to utilize PVDF as a sensor, the polymer must be converted from typical alpha phase to beta phase prior to electrostatic poling. This research focuses on the in situ characterization of mechanical activation of the beta phase in a PVDF-based latex films using in situ Raman spectroscopy for real time monitoring of PVDF phase content. The spray deposited PVDF latex paint films were experimentally characterized as free standing thin films drawn in a tensile stage while in-situ measurements were taken with Raman spectroscopy at a wavelength of 532 nm. The Raman spectrum of each phase of PVDF is known to be unique and can be used to correlate the amount of alpha and beta phases in the characterized film during and after phase transition. The stress and strain data from the tensile stage will be associated with the in situ Raman spectra of the PVDF, providing a relationship between stress, strain, and beta phase content in these PVDF latex paint films.

9061-75a

Design and creation of embeddable multifunctional 3D sensory systems for integrated structural damage monitoring of advanced composite

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Integrated sensory system has been employed for Structural Health Monitoring (SHM) of advanced engineering composites. This innovative approach is being considered for future SHM applications in civil and aerospace application. Currently, wired sensor networks are still the most prevalent systems employed for SHM. The functionalized carbon nanotubes (CNT) yarns demonstrate excellent mechanical, electronic, and catalytic properties, which exhibit high surface area with enhanced optoelectronic and electronic performance. A yarn-shaped and high efficiency 3D sensor has been developed using coaxial, inter-aligned, ultrastrong and highly conductive CNT yarns in both electrodes with solid phase hole and electron transferring media. The hydrothermally crystallized TiO2 film along with interfaced quantum-dot has been grafted around the working electrode, which was found capable in wide range of structural flexibility without changing signal transmitting capability. The signal conversion efficiency is independent of sensor shape, position and environmental condition. Due to the three dimensional feature with highly structural flexibility and inter-connectivity, the CNY sensors can easily be woven into reinforced carbon fabric for advanced composite. This embeddable intrinsic sensory system opens an innovative approach of aerospace system's SHM.

9061-36b

Application of image analysis and time-frequency analysis for tracking the rotating blades vibration

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Most of structural health monitoring and experimental researches rely heavily on physical sensors to acquire data. For three dimensional, non-linear, large acceleration rigid-body motion these physical sensors have their limitation. A different solution by using computer vision methods can avoid these limitations. Using computer vision to extract 3D motion the photogrammetry is one of the measurement techniques that use photographs to establish the geometrical relationship between a three-dimensional (3D) object and its two- dimensional (2D) photographic images. The objective of this paper is to investigate the application of the photogrammetric approach to measuring the vibration of a research-scale model wind turbine blades (both rigid and flexible blades). In order to control the excitation (rotation of the wind turbine blades), a motor was used to spin the blades at controlled angular velocities. Due to the acceleration and de-acceleration effect, the out-of-plane motion of blade can be induced. Two cameras are set in front of the turbine to tape the video images. Through a sequence of stereo image pairs acquired by high speed camera, the images are studied. The cameras we used are the SONY NEX FS700 with 960 fps. Before taking the photos camera calibration was conducted which include lens distortion and skew factor is examined. To analyze the displacement of the motion target on the turbine blade, after loading the 3D calibration, the 3D positions are calculated by using a stereo triangulation technique. Time-frequency techniques were employed to observe the change of vibration frequencies. Image measurement error induced by image analysis error and camera synchronization error was discussed. Then the displacement fields by image template matching can be calculated. Finally, this paper will conclude with the results of monitoring the rotation and translation (both in-plane and out-of-plane) of a rotating flexible wind turbine blade due to controlled angular velocity.

9061-37b

Air-coupled ultrasound and laser vibrometry for damage detection in composites

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Conventional ultrasound inspection has been a standard non-destructive testing method for providing an in-service evaluation and noninvasive means of probing the interior of a structure. In particular, measurement of the propagation characteristics of Lamb waves allows inspection of plates that are typical components in aviation industry. In most cases, a coupling medium is required between the transducer and any inspected specimen to minimize the acoustic impedance mismatch at the boundary.

A fully automated, rapid, non-contact approach for excitation and detection of Lamb waves is presented and applied for non-destructive evaluation of composites. An air-coupled transducer excites ultrasonic waves on the surface of a plate, generating different propagating Lamb wave modes depending on the incident angle of the transducer. The second air-coupled transducer detects the incident mode or other modes formed by interaction with defects. The receiving transducer is used in combination with a Laser Doppler Vibrometer to measure both the in-plane and out-of-plane Lamb wave modes of the composite plate.

This technology, based on direct waveform imaging, focuses on measuring dispersive curves, characterizing material anisotropy and locating damages in the inspected structure. The analytical tools consist of a Fourier transform that converts the time-space waveform data into a frequency-wavenumber domain and a filter that isolates the waves backscattered by any discontinuity in the plate.

The combination of air-coupled and laser vibrometry detection of Lamb waves improves the traditional waveform imaging technique to include not only the dominant out-of-plane displacement but also in-plane displacement captured by an accurately positioned air-coupled transducer.

9061-39b

Air-coupled guided wave detection and wavenumber filtering to full-field representation of delamination in composite plates

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In this work, leaky guided waves are used to detect delamination in composite plates. Delaminations produce guided waves scattering, local resonances and eventually mode conversion. Indeed, detecting and analyzing these phenomena may be relevant for plate characterization. To such purpose, a hybrid ultrasonic set-up and a dedicated signal processing are proposed.

The experimental apparatus uses a piezoelectric transducer to generate acoustic guided waves in the composite plate, and an air-probe with a proper lift-off to detect the leakage in terms of air pressure wave over the plate surface. For each position of the air-probe, multiple acquisitions are averaged to increase the SNR.

The processing is based on the projection of the acquired wave in the Curvelet Transform (CT) domain. The CT is a special member of the family of multiscale and multidimensional transforms. Thanks to the spatial and temporal localization of curvelets, it is possible to decompose waves that are overlapped both in the time/space and in the frequency/wavenumber domain. In the proposed approach, such property is exploited to remove from the data the information related to the incident wave field, emphasizing thus the information of leaky guided waves scattered by the delamination.

An application on a 4.9 mm thickness composite laminate impacted with 21 Joule, is proposed. Results show how the leakage of guided wave can be used to detect contactless the presence of delamination.

9061-40a

Dynamic characterization of a soft elastomeric capacitor for structural health monitoring applications

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A novel thin film sensor consisting of a soft elastomeric capacitor (SEC) for meso-scale monitoring has been developed by the authors. Each SEC transduces surface strain into a measurable change in capacitance. In previous work, the authors have shown that the performance of the SEC compares well with conventional resistance-based strain gages, providing a resolution of 25 ?? using an inexpensive off-the-shelf data acquisition system for capacitance measurements. Here, we further the understanding of the thin film sensor by characterizing its dynamic behavior. The SEC is subjected to dynamic loads in both axial and bending modes. The study of wavelet transforms indicates that the sensor can be used to identify dynamic inputs. Laboratory tests conducted on a large-scale beam show that the sensor can be used to detect fundamental modes. Overall results demonstrate the promising capabilities of the thin film sensor at dynamic monitoring of civil structures.

9061-41a

Thin film sensor network for condition assessment of wind turbine blades

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Existing sensing solutions facilitating continuous condition assessment of wind turbine blades are limited by a lack of scalability and clear link signal-to-prognosis. With recent advances in conducting polymers, it is now possible to deploy network of thin film sensors over large areas, enabling low cost sensing of large-scale systems. Here, we propose to use a novel sensing skin consisting of a network of soft elastomeric capacitors (SECs). Each SEC acts as a surface strain gage transducing local strain into measurable changes in capacitance. Using surface strain data facilitates the extraction of physics-based features from the signals that can be used to conduct condition assessment. We demonstrate that the SEC network can be used effectively for reconstructing deflection shapes. While the SEC network tends to underestimate deflections because it averages surface strain over its area, results from the reconstructed normalized deflection shapes show that the novel technology outperforms off-the-shelf resistive strain gages due to this averaging particularity that minimizes the effects of sensor placement errors.

9061-42a

Electromechanical models of carbon nanotube-polyelectrolyte thin films guided by microscopy

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Over the last few decades, carbon nanotube (CNT)-based thin films or nanocomposites have been widely investigated as a multifunctional material. The proposed applications extend beyond sensing, ultra-strong coatings, biomedical grafts, and energy harvesting, among others. In particular, thin films with a percolated and random distribution of CNTs within a flexible polymeric matrix have been shown to change its electrical properties in response to applied strains. While a plethora of experimental work has been conducted, modeling their electromechanical response remains challenging. For example, straight and curved fibers that represent nanotubes have been incorporated in electromechanical models, but these structures may not accurately represent CNT morphology at the nano- and micro-scales. Thus, the objective of this study was to utilize direct observations of the physical properties of CNTs and then to incorporate them in a percolation-based numerical model. First, a layer-by-layer technique was used for fabricating CNT-polyelectrolyte thin films. Second, scanning electron microscopy (SEM) and atomic force microscopy (AFM) were employed for characterizing the as-deposited CNT physical properties. The CNTs' lengths, diameters, and shapes were extracted from these images. Then, a series of representative shapes was constructed to represent the as-deposited CNTs. An electromechanical percolation-based model was then implemented in MATLAB (that includes the experimentally observed statistical distribution of CNT lengths and diameters). The model was used for computing thin film electrical conductivity and its strain-sensitive response, and the results were compared to experimental measurements. Lastly, the numerical results were also compared to models that did not account for nanotube shapes.

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9061-43a

Design and characterization of a Piezoelectric sensor for monitoring scour hole evolution

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Scour occurring near bridge piers and abutments jeopardizes the stability and safety of overwater bridges. In fact, bridge scour is responsible for a significant portion of overwater bridge failures in the United States and around the world. As a result, numerous methods have been developed for monitoring bridge scour by measuring scour depth at locations near bridge piers and foundations. Besides visual inspections conducted by trained divers, other technologies include sonar, float-out devices, magnetic sliding collars, tilt sensors, and fiber optics, to name a few. These systems each offer unique advantages, but most of them share fundamental limitations (e.g., high costs, low reliability, limited accuracy, low reliability, etc.) that have limited their implementation in practice. Thus, the goal of this study is to present a low-cost and simple scour depth sensor fabricated using piezoelectric poly(vinylidene fluoride) (PVDF) polymer strips. Unlike current piezoelectric scour sensors that are based on mounting multiple and equidistantly spaced transducers on a rod, the proposed sensor is formed by coating one continuous PVDF film onto a substrate, followed by waterproofing the sensor. The PVDF-based

sensor can then be buried in the streambed and at a location where scour depth measurements are desired. When scour occurs and exposes a portion of the PVDF sensor, water flow excites the sensor to cause the generation of a time-varying voltage signal. Since the dynamics of the voltage time history response is related to the exposed length of the sensor, scour depth can be calculated. This study presents the design and fabrication of the sensor. Then, the sensor's performance and accuracy is characterized by conducting laboratory experiments (i.e., in ambient air and in a flume with soil and flowing water). Experimental results are also compared to COMSOL multi-physics numerical simulations.

9061-44a

Cracks monitoring and characterization by Ba0.64Sr0.36TiO3 flexoelectric strain gradient sensors

Wenbin Huang, Xiaoning Jiang, Fuh-Gwo Yuan, Michael Yang, North Carolina State Univ. (United States)

Cracks could cause catastrophic failure of mechanical, civil, and aerospace structures. Stress intensity factors of the cracks are mostly monitored to ensure the operation safety of structures. Different with present techniques that characterize the stress intensify factors through measuring deformation or stress/strain, flexoelectric effect suggests another method for accurate assessment by recording the strain gradient distributions, which are usually the most sensitive measurand near the crack.

In this work, Ba0.64Sr0.36TiO3 flexoelectric strain gradient sensors were adopted for measurement of stress intensify factors of cracks. Firstly, mixed mode asymptotic strain gradient field in the vicinity of crack tip was analyzed. Induced flexoelectric polarization in the strain gradient sensors attached nearby was derived. It was found that the stress intensity factors and non-singular component featuring cracks can be evaluated using the measured strain gradient. To verify the analytical model for measurements of crack intensity factors through strain gradient, a specimen with Mode-I crack was then prepared with two strain gradient sensors (4.7 mm ? 0.9 mm ? 0.3 mm) attached close to the crack tip. The experimental results were in accordance with the empirical estimation showing the difference less than 13 %, confirming that flexoelectric strain gradient sensing can be a good avenue for measuring the stress intensify factors by using reduced numbers of sensors, thus in-situ monitoring the cracks development.

9061-45b

Residual stress measurement of butt-weld zone for shipbuilding materials using laser speckle interferometry

Hyunchul Jung, Taeho Choi, Kyeongsuk Kim, Chosun Univ. (Korea, Republic of)

Welding is most joint method for making a structure in the shipbuilding industry. Because the weld zone including heat affected zone (HAZ) is formed by very intense heat, the residual stress must exist in this zone. Welding structures contains the residual stress before any loading conditions applied. The residual stress causes some critical problems such as brittle failure, fatigue failure, stress corrosion cracking, buckling, etc. Many measurement techniques have been developed to analyze the residual stress itself and effects of residual stress to a welding structure quantitatively. In this study, laser speckle interferometry (LSI) which is one of nondestructive testing methods is used for analyzing the residual stress distribution in thickness plane. The thick butt-welding specimens of the shipbuilding material are fabricated and the entire displacement of measuring plane is obtained by tensile loading using UTM and LSI. From the experimental result, the strain of the base metal and the weld zone is measured and the elastic modulus can be calculated. A method for measuring the residual stress using the differences of between the strain of the base metal and that of the weld zone that was already proposed through the Korean patent is applied to quantitatively measure the residual stress of the weld zone. The result is compared with that of ultrasound testing.

9061-46b

Noncontact visualization of nonlinear ultrasonic modulation for reference-free fatigue crack detection

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This paper presents a fatigue crack detection technique based on visualization of nonlinear ultrasonic wave modulation produced by fatigue crack. When distinctive low frequency (LF) and high frequency (HF) inputs are generated and applied to a structure, the presence of a fatigue crack can provide a mechanism for nonlinear ultrasonic modulation and create spectral sidebands around the frequency of the HF signal. In this study, the two input signals are created by a single dual PMN-PT transducer, and the corresponding ultrasonic responses are scanned over the target area using a laser Doppler vibrometer (LDV). Then, the crack-induced spectral sidebands are isolated using a combination of linear response subtraction (LRS), synchronous demodulation (SD) and continuous wavelet transform (CWT) filtering. Then, the target structure is scanned using LDV, and the extracted spectral sideband components are visualized near the fatigue crack. The effectiveness of the proposed noncontact scanning technique is tested using an aluminum specimen with a real fatigue crack.

9061-48b

A vision-based approach for obtaining the time-varying displacement field of vibrating systems

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This study presents the results of an extensive analytical and experimental investigation to develop, calibrate, implement, and evaluate the feasibility of a novel vision-based approach for measuring the absolute displacement time history at numerous locations of vibrating dynamic systems that leads to the extraction of the associated time-varying displacement field. The measurements were obtained using a combination of a camera and a cost-effective depth sensor. Calibration of the vision system was conducted to match the RGB pixels with the corresponding depth values, and to compensate for the lens distortion. It is shown that the proposed approach can potentially be used as an economical and robust solution for obtaining the evolving displacement field in realistic civil, mechanical, and aerospace structural systems undergoing time-varying complex three-dimensional deformations.

9061-49b

Noncontact monitoring of fatigue crack growth using high frequency guided waves

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The development of fatigue cracks at fastener holes due to stress concentration is a common problem in aircraft maintenance. This contribution investigates the use of high frequency guided waves for the non-contact monitoring of fatigue crack growth in tensile, aluminium specimens. High frequency guided ultrasonic waves have a good sensitivity for defect detection and can propagate along the structure, thus having the potential for the inspection of difficult to access parts by means of non-contact measurements. Experimentally the required guided wave modes are excited using standard wedge transducers and measured using a laser interferometer. The growth of fatigue cracks during cyclic loading was monitored optically and the resulting changes in the signal caused by crack growth are quantified. Full three-dimensional simulation of the scattering of the high frequency guided ultrasonic waves at the fastener hole and crack has been implemented using the Finite Difference (FD) method. The comparison of the results shows a good agreement of the measured and predicted scattered field of the guided wave at quarter-elliptical and through-thickness fatigue cracks. The measurements show a good sensitivity for the early detection of fatigue damage and for the monitoring of fatigue crack growth at a fastener hole. The sensitivity and repeatability are ascertained, and the robustness of the methodology for practical in-situ ultrasonic monitoring of fatigue crack growth is discussed.

9061-50a

Damage sensitive features in seismically damaged steel beam-column connection extracted in ambient vibration testing

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This paper presents the changes in the dynamic characteristics of steel beam-column connections under seismic cyclic loading and damage sensitive features extracted from ambient vibration testing of the damaged connections. Beam-column connection specimens were loaded with a gravity-frame that supported large fictitious mass. This specifically-designed test configuration enabled the ambient vibration testing of the specimen at natural frequency ranges of mid-rise steel buildings. In the tests, quasi-static cyclic loading was conducted to beam-end fracture. At each loading cycle, the specimen was unloaded and excited dynamically with white-noise using a modal shaker installed on top of the gravity-frame.

Three one-quarter-scaled specimens were tested and the dynamic characteristics were monitored using MEMS accelerometers and dynamic PVDF strain sensors. Test results showed different damage sensitive features for various damage patterns including concrete floor slab cracks, flange and web local buckling, beam global buckling, and beam-end fracture. For example, the natural frequency of a specimen with floor slab dropped significantly as concrete crack progressed while the reduction in the natural frequency was relatively small for local buckling, beam global buckling and small beam-end fracture. The test results indicated the importance of the selection of damage sensitive features that are appropriate for the damages in interest.

9061-51a

Multi-metric model-based structural health monitoring

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The inspection and maintenance of bridges of all types is critical to the public safety and often critical to the economy of a region. Recent advanced sensor technologies provide accurate and easy-to-deploy means for structural health monitoring and, if the critical locations are known a priori, can be monitored by direct measurements. However, for today's complex civil infrastructure, the critical locations are numerous and often difficult to identify. This paper presents an innovative framework for structural monitoring at arbitrary locations on the structure combining computational models and limited physical sensor information. The use of multi-metric measurements is advocated to improve the accuracy of the approach. A numerical example is provided to illustrate the proposed hybrid monitoring framework, particularly focusing on fatigue life assessment of steel structures.

9061-52a

Response estimation of a building subject to a large earthquake using acceleration data of a single floor recorded by a sensor agent robot

Akira Mita, Yushi Shinagawa, Keio Univ. (Japan)

The Great Tohoku Earthquake hit northern Japan on March 11 in 2011. The moment magnitude of the earthquake was 9.0. Due to this large energy release, many buildings especially with long natural periods such as tall buildings and isolated buildings had been shaken for long duration more than 10 minutes in Tokyo. Although no fatal damage was reported there, many furnitures and ceiling systems fell down and residents in the buildings felt fear of total collapse. Such long duration of the shaking in the long period components had not been considered when most buildings were designed. On several buildings structural health monitoring system provided real-time information on the safety of the buildings. In such cases, the residents did not feel any danger of collapse at all as they could immediately know the level of the response and the impacts.

Considering the importance of knowing the danger of the building immediately after the earthquake, the study proposes two algorithms for estimating the maximum response of a building when subject to a devastating earthquake only using a sensor equipped with a sensor agent robot situated on an arbitrary floor of the building. The first algorithm is for normal buildings. The second one is for base isolated structures. The algorithms do not require the information on the input motion. The sensor agent robot may be used for other purposes such as security and lighting control under normal circumstances. Thus the proposed algorithms are very useful tools for a robot-based structural health monitoring system.

9061-53a

Multisensor fusion for system identification

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System identification is a fundamental process for developing a numerical model of a physical structure. The system identification process typically involves in data acquisition; particularly in civil engineering applications accelerometers are preferred due to its cost-effectiveness, low noise, and installation convenience. Because the measured acceleration responses result in translational degrees of freedom (DOF) in the numerical model, moment-resisting structures such as beam and plate are not appropriately represented by the models. This study suggests a system identification process that considers both translational and rotational DOFs by using accelerometers and gyroscopes. The proposed approach suggests a systematic way of obtaining dynamic characteristics as well as flexibility matrix from two different measurements of acceleration and angular velocity. Numerical simulation and laboratory experiment are conducted to validate the efficacy of the proposed system identification process.

9061-54a

Parametric time-domain identification of civil engineering structures with multiple inputs using decoupled output signals

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Civil engineering structures are often subjected to multi-directional actions such as earthquake ground motion, which lead to complex structural responses. The contributions from the latter multi-directional actions to the response are highly coupled, leading to a Multiple-Input, Multiple-Output (MIMO) system identification problem. Compared with Single-Input, Multiple-Output (SIMO) system identification, MIMO problems are more computationally complex and error-prone. In this paper, a new system identification strategy is proposed for civil engineering structures with multiple inputs that induce strong coupling in the response. The proposed solution comprises converting the MIMO problem into separate SIMO problems, decoupling the outputs by extracting the contribution from the respective input signals to the outputs. To this end, a QR factorization-based decoupling method is employed, and its performance is examined. Three factors which affect the accuracy of the decoupling result, including memory length, input correlation, and system damping, are investigated. Additionally, a system identification method which combines the AutoRegressive model with eXogenous input (ARX) and the Eigensystem Realization Algorithm (ERA) is proposed. The associated Extended Modal Amplitude Coherence (EMAC) and Modal Phase Collinearity (MPC) are used to delineate the structural and noise modes in the fitted ARX model. The efficacy of the ARX-ERA method is then demonstrated through identification of the modal properties of a highway overcrossing bridge.

9061-56b

A robust baseline removal method for guided wave damage localization

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Guided waves can propagate long distances and are sensitive to subtle structural damage. Guided-wave based damage localization often requires extracting the scatter signal(s) produced by damage, which is typically obtained by subtracting an intact baseline record from a record to be tested. However, in practical applications, environmental and operational conditions (EOC) dramatically affect guided wave signals. In this case, the baseline subtraction process can no longer perfectly remove the baseline, thereby defeating localization algorithms.

In our previous research, we showed that singular value decomposition (SVD) can be used to detect the presence of damage under large EOC variations, because it can differentiate the trends of damage from other EOC variations. This capability of differentiation implies that SVD can robustly extract a scatter signal that is not affected by temperature variation. Therefore, it is a baseline-free alternative of the current “temperature compensation and baseline subtraction” routine for damage localization.

In the work summarized in this paper, we collect pitch-catch records from randomly placed PZT transducers on an aluminum plate while undergoing temperature variations. Damage is introduced to the plate during the monitoring period. We then use our SVD method to extract the scatter signal from the records, and use the scatter signal to localize damage using the delay-and-sum method. To compare results, we also apply several temperature compensation methods to the records and then perform baseline subtraction. We compare the localization results using scatter signals from the SVD and temperature-compensated baseline subtracti

9061-57b

Extraction of a series of novel damage sensitive features derived from the continuous wavelet transform of input and output acceleration measurements

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This paper proposes a series of novel Damage Sensitive Features for earthquake damage estimation. The features take into account input (ground motion) and output acceleration (structure response) measurements. The Continuous Wavelet Transform is applied to both acceleration signals in order to obtain both time- and frequency domain resolution. It is demonstrated that the deconvolution of the two Transforms contains information inherent to the structure’s state during the response. The Maximum Entropy Method, which is widely used in fields such as astronomy and medical imaging is used to obtain a solution to the deconvoluton problem. In particular, an algorithm that makes use of Lagrange multipliers is implemented. The Damage Sensitive Features are then derived through statistical processing of the resulting matrix. This algorithm has been applied on data acquired from shake table tests where the structures were subjected to progressive damage. The proposed features are compared to response quantities that are indicative of damage (such as the dissipated hysteretic energy) and show remarkable correlation with the extent of damage. The data utilized has not been pre-processed, illustrating the robustness of the algorithm against sensor noise. The proposed algorithm has several advantages: Minimal input and knowledge of the structure is required. More information on the structure’s state is extracted through use of both the input and output signals. Only the strong motion is used, allowing for results immediately after an earthquake and, finally, only two acceleration measurements are required to obtain a damage estimate, resulting in easier sensor deployment.

9061-58b

Toward characterization of the effects of environmental and operational conditions (EOC) on diffuse-field ultrasonic guided-waves in pipes

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In spite of many favorable characteristics of guided-waves for Nondestructive Evaluation (NDE) of pipes, their multi-modal, dispersive, and multi-path characteristics result in complex signals whose interpretation is a difficult task. In addition, one of the main challenges in real-world application of guided-waves based systems for pipelines is their sensitivity to changes in environmental and operational conditions (EOC) that these structures are subject to.

In a large number of current guided-wave based damage detection approaches, variation of EOCs are either ignored or controlled throughout the experiments. Studies that have considered the effects of EOC variations either fail to reflect realistic EOC scenarios (i.e. limited to particular effects of specific EOCs, like time shifting effects of temperature) or lack the necessary link between the effects of EOC variations and different aspects of developed approaches, which limits their extensibility. These shortcomings motivate in-depth and formal investigation on the effects of different EOC scenarios on diffuse-field guided-waves recorded from complex structures like pipes, under varying EOCs.

This paper presents various methods to motivate characterizing the effects of varying EOCs, namely temperature and flow rate, on diffuse-field ultrasonic guided-waves propagating through pipes. Diffuse-field pitch-catch data recorded from fully operational hot water piping system of a campus building are used to demonstrate and verify the effects of these EOCs. The observed effects of temperature and flow rate on (1) metrics reflecting different physical aspects of the waves, on (2) independent components of the signals, extracted through Independent Component Analaysis, and on (3) the performance of linear classifiers, such as a sparse representation, strengthen the results of our gap analysis.

9061-59b

Damage diagnosis using improved Hilbert Huang transform on a non-stationary signal

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This study proposes a damage sensitive feature (DSF) to detect damage in a structure subjected to non-stationary excitation. Till now, structural damage diagnosis literature comprised mainly of signal processing techniques which assume the stationarity of the signal. However, for responses during extreme events like an earthquake or hurricane, that assumption does not hold valid. Ensemble Empirical Mode Decomposition (EEMD) with Hilbert transform is an innovative way to analyze non-stationary and non-linear signals and shows more promise than traditional frequency and time domain techniques in the aspect of time-frequency/ time-scale resolution. Also, EEMD comes under the class of noise assisted data analysis methods, in which white noise is added to the existing non-stationary signal to provide a uniform reference frame in the time-frequency space and the sifting process done thereafter produces dyadic scale signals which are equivalent of intrinsic mode functions (IMF). Subsequently, statistical significance tests are conducted to establish the relevance of the obtained IMFs. DSF is then modeled as a function of energy represented by IMFs at a particular time instant.

The performance of the proposed DSF is validated using data from a shake table test performed on a four-story steel moment-resisting frame, subjected to the scaled ground motions of the 1994 Northridge earthquake. The results show that DSF value increases with the extent of damage. Along with the simulation results, a sensitivity analysis done by the varying number of IMFs, demonstrates that the proposed DSF is a novel and useful tool for damage detection and post-seismic structural evaluation.

9061-60b

BOES: building occupancy estimation system using sparse ambient vibration monitoring

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Many ubiquitous computing and building maintenance systems call for occupancy knowledge. However, current systems that offer occupancy information often require finer than room-level infrastructure supports, utilizing an array of sensors, such as cameras and infrared sensors. Furthermore, these infrastructures can be expensive and labor-intensive to deploy and maintain. To address these challenges, we propose BOES, a room-level building occupancy estimation system that exploits existing building structure health monitoring (SHM) systems to estimate room-level occupancy and activity-level without additional sensing infrastructures. Although sensors in SHM systems are sparse and noisy for occupancy estimation purpose, BOES overcome these issues by utilizing high frequency sensor readings and building layout characteristics. To achieve our goals, our system performs the following steps: 1) the building ambient vibration signals are collected from floors and walls using multiple accelerometers; 2) various vibration signatures are extracted from the collected data, including activities such as footsteps, opening/closing of doors, general building vibrations, etc.; and 3) the occupancy of each space is estimated from the vibration signatures and the space layout using machine-learning techniques. We evaluate the system performance by investigating head-count errors and tracking errors for occupant trajectories collected through both BOES and manual survey. The evaluations mainly focus on two deployments: 1) a small-scale experiment on one floor of a multi-story building at Carnegie Mellon University in Pittsburgh, USA; and 2) a large-scale experiment using a SHM system of the 11-story Rohm Hall at Tsinghua University in Beijing, China.

9061-61b

Oriented wireless sensing: algorithms for estimating damage sensitive features

Mark Mollineaux, Ram Rajagopal, Stanford Univ. (United States)

Structural Health Monitoring (SHM) demands efficient and rapid sensing of damage in a structure. Recent methods relying on pattern analysis are able to utilize direct acceleration measurements from sensors attached to the structure to determine damage in an effective way. Yet such methods can fail in application scenarios where structures experience permanent deformations or are undergoing significant motion. Moreover, classic damage modeling suggests that hard to measure direct displacements are better determinants of damage than acceleration measurements. Yet it is quite hard to obtain direct displacement measurements from accelerometers due to various sources of measurement noise and bias. Recently, Oriented Wireless Sensing was proposed as a new sensing approach to overcome these limitations by fusing several sensor measurements that provide independent measurements of orientation, for example accelerometers, gyros and magnetometers. The system can be easily built into a wireless module by utilizing MEMS technology. The initial study demonstrated the feasibility and accuracy of direct displacement estimation utilizing a simple Kalman Filtering approach.

In this paper, we progress the development of the method by designing novel and improved fusion algorithms for orientation and displacement estimation that are able to account for several practical relevant scenarios: a rotating frame of reference and a permanently deflected beam. In particular we design state-space estimation filters that range from standard to more sophisticated ones that incorporate elements of structural engineering theory. We then combine typical damage sensitive feature (DSF) extraction methods to the output of such filters to yield a direct damage state sensor that is more accurate and capable of operating under challenging conditions. The performance of the algorithms is compared through application to a calibration experiment performed on a shake table and other additional measurements.

9061-136

Application of genetic mechanism for faster evolution of building reflecting environmental factors

Saya Nishikawa, Akira Mita, Keio Univ. (Japan)

In recent years, people's environmental awareness has been raised due to the global warming and the energy problems, and the energy-saving life is now a major matter of concern. In addition, the diversity of people's living style led strong demand for smart living environments which respond to each individual's needs. Considering these backgrounds, many research works of Intelligent Spaces have been conducted. However, most studies assume prescribed scenarios, so that unexpected situations are not properly considered.

Therefore, we suggest "Biofied Building" which realizes more comfortable, safer and more energy-efficient space by learning from the system of living things. Living things have been surviving over the years by making full use of their adaptive functions and have been evolving under various environmental events retaining genetic and phenotypic diversity. In this paper, we focus on evolutionary adoption and propose a new genetic mechanism for building design. This mechanism reflects past experiences, such as characteristics of the environment and discomfort of residents, which are obtained by sensor agent robots. As a result, the next generation will have a higher fitness feature to the surrounding environment. This mechanism suggests the best design specifications of a new building when it is rebuilt. The living space will become more suitable for each resident. The proposed mechanism can realize the faster evolution.

9061-137

High-temperature measurement using Cu-plating fiber Bragg grating for metal smart structure applications

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The commonly used coating for fiber Bragg gratings (FBGs), with Acrylate as its main component, is not able to endure high temperature and is used only under 100°C. With polyimide coating it can measure temperature up to 300°C. However, the relationship between the FBG's central wavelength shift and temperature variation is not linear by quadratic, once the measured temperature is above 100°C, which restricts FBG's application in measuring high temperature. To improve FBG's temperature characteristics, we covered FBG's surface with copper uniformly by way of electroless Cu-plating, and carried out high temperature experiments to validate the feasibility of high temperature measurement and obtained good results.

Our high-temperature experiments for electroless Cu-plating FBG indicate that Cu-plating FBG can measure high-temperature up to (even beyond) 300°C, and it has high linearity, accuracy and repeatability. In a certain range, FBG's thermal expansion coefficient increases with increase in the Cu-plating thickness, so we can obtain specific Cu-plating FBG's temperature sensitivity by controlling the plating layer's thickness. The temperature sensitivity of FBG with Cu-plating can be improved by more than three times with no less than 300 micrometers thick coating by electroless and electrical Cu-plating. Such Cu-plating FBG can be soldered onto metal structures to get good bonding with the structure. As a result, the Cu-plating FBG sensors soldered with metal structure can get good protection, and can be bonded with metal structure perfectly to constitute metal smart structure with high-temperature monitoring. It will pave a new way for fiber smart metal structures and materials.

9061-138

Watt-linkage based sensors for low frequency motion measurement and control of spacecrafts and satellites

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This paper describes a new mechanical application of the Watt-linkage for the development and implementation of a new class of mono/triaxial sensors aimed to low frequency motion measurement and control of spacecrafts and satellites. The basic element of these sensors is the one dimensional UNISA seismometer/accelerometer based on the classic Watt-linkage configured as Folded Pendulum monolithic FP sensors in absence of gravity, suitably geometrically positioned. Applications of specialized versions of this sensor already exist in the field of earthquake engineering, geophysics and civil engineering requiring large band-low frequency performances coupled with high sensitivities.

9061-139

Advances in Barkhausen noise analysis

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The magnetic Barkhausen Noise technique is a well suited method for the characterization of ferromagnetic materials. The Barkhausen effect results in an interaction between the magnetic structure and the microstructure of materials, and is sensitive to the stresses and microstructure related mechanical properties. Barkhausen noise is a complex signal that provides a large amount of information, for example frequency spectrum, amplitude, RMS value, dependence of magnetic field strength, magnetization frequency and fractal behavior. Although this technique has a lot potentials, it is not commonly used in nondestructive material testing. Large sensors and complex calibration procedures made the method impractical for many applications. However, research has progressed in recent years; new sensor designs were developed and evaluated, new algorithms to simplify the calibration and measurement procedures were developed as well as analysis of additional material properties have been introduced.

This paper summarizes several modifications of the material characterization principle using current injection techniques, electric potential noise, magnetic after-effects and fractal analysis, respectively.

9061-140

The state of the art on innovative monitoring system in Korea

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In Korea, various kind of innovative sensing technology and infrastructure application have performed nowadays. Especially, development on high resolution and accuracable wireless sensors, fire detection system by using optical fiber sensor, image processing technologies for detecting crack of concrete structures have performed since 2011.

In addition, safety evaluation algorithm for real-time monitoring of abnormal structural behavior have developed in this project. For the operation system, platform and standardization are considered. By using this platorm system, all kinds of developing technologies and algorithms can be integrated, and the other kinds of monitoring system can be included and connected in that platform system. In 2014 and 2015, test bed integration is scheduled for bridge or tunnel. Finally these developing systems may be applied to infrastructure effectively for the safety, and the loss of life and properties may be decreased by using this system.

9061-141

Natural frequency identification of smart washer by using adaptive observer

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Bolted joints are widely used in machines/structures. However, many serious accidents occur because of bolt loosening.

Constantly monitoring system for the bolt loosening is immediately expected.

The smart washer has been proposed in order to detect remotely and automatically the loosening of the bolted joint.

The smart washer has a shape of the cantilever beam, and enables an

active sensing by the piezoelectric material.

We noted that the natural frequency for the smart washer is varying by depending on the tightening axial tension.

This study has been proposed two approaches for the natural frequency analysis of smart washer, one is a system identification, the other is a supervision system by using multiple observers.

The system identification has the problems that the fault detection accuracy degrades due to the influence of identification error, and that the choice of the identification parameters depends on an experience.

On the other hand, the supervision system has the problems that prepared observers are the discreteness to loosening level, hence, the bolt loosening detection accuracy depends on division number of observers.

A novel natural frequency analysis method by adopting adaptive observer is proposed in this paper.

The numerical simulations and the experimentations are performed to verify the influence of the initial parameter and the adaptive gain. Improvement of bolt loosening detection accuracy will be confirmed by comparing the proposed method with the previous method.

9061-142

A novel ionizing radiation sensor utilizing radiophotoluminescence in silver-doped phosphate glass

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The objective of this study is to investigate the properties of radiophotoluminescence (RPL) in the Ag-doped phosphate glass (glass dosimeter), which is now used as individual radiation dosimeter.

The RPL emission and excitation spectra, photoluminescence (PL) spectra and optical absorption spectra before and after irradiation with x-ray, alpha-ray or heavy ions were investigated. It was found that the RPL intensity was linearly increased with increasing x-ray irradiation dose up to 15 [Gy], which indicating that the Ag-doped phosphate glass can use as high sensitive solid state radiation sensor.

In the basis of RPL properties obtained, the emission mechanism of RPL in Ag-doped phosphate glass as well as the radiation particle discrimination using RPL spectrum was discussed.

Furthermore, the application to the monitoring of contamination due to radioactive materials and the usefulness of Ag-doped phosphate glass dosimeter in decontamination task for restoration of residence area near Fukushima Nuclear Power Plant were also discussed.

9061-143

Design of overload vehicle monitoring and response system based on DSP

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The usage of road and bridge is increasing exponentially with the development of social economy. The overload vehicles are making much more damage to the road surface than the regular ones, which can cause premature fatigue of the road and bridge. Many roads and bridges are equipped with structure health monitoring system(SHM) to provide early-warning to these damage and evaluate the safety of road and bridge. However, because of the complex nature of SHM system, it's expensive to manufacture, difficult to install and not well-suited for the regular bridges and roads . Based on this application principle, this paper designs a compact structure health monitoring system based on DSP, which is highly integrated, low-power, easy to install and inexpensive to manufacture.

The system will mainly use the dynamic real-time data collected from the sensors arrays imbedded under the surface of road and bridge, and combine with the current damage analysis to estimate the bearing capability of the road and bridge. The designed system is divided into sensor arrays, the charge amplifier module, the DSP processing unit, the alarm system for overload and the estimate for damage of the road and bridge structure. Sensor arrays include a method for laying sensors under the ground that can accurately identify vehicles, and monitor their weights in heavy traffic. Then, the signals coming from sensor arrays go through the charge amplifier. DSP processing unit will receive the amplified signals, estimate whether it is an overload signal or not, and convert analog variables into digital ones so that they are compatible with the back-end digital circuit for further processing. The system will also restrict certain vehicles that are overweight, including taking image sampling and sending off alarm for vehicles in violations, and transferring the collected pressure data to remote data center for further structure health monitoring analysis by rain-flow counting method. Experimental results show that the pressure monitoring error rate for vehicles in normal speed is under 10% and the system can accurately monitor the real-time overload of road and bridge. Besides, the miniaturization structure of the system will also make it easy to manufacture and save the cost of structure health monitoring.

9061-144

A novel high pressure, high temperature vessel used to conduct long-term stability measurements of silicon MEMS pressure transducers

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The need to quantify and to improve long-term stability of pressure transducers is a persistent requirement from the aerospace sector. Specifically, the incorporation of real-time pressure monitoring in aircraft landing gear, as exemplified in Tire Pressure Monitoring Systems (TPMS), has placed greater demand on the pressure transducer for improved performance and increased reliability which is manifested in low lifecycle cost and minimal maintenance downtime through fuel savings and increased life of the tire.

Piezoresistive (PR) silicon MEMS pressures transducers are the primary choice as a transduction method for this measurement owing to their ability to be designed for the harsh environment seen in aircraft landing gear. However, these pressure transducers are only as valuable as the long-term stability they possess to ensure reliable, real-time monitoring over tens of years. The “heart” of the pressure transducer is the silicon MEMS element, and it is at this basic level where the long-term stability is established and needs to be quantified.

A novel High Pressure, High Temperature (HPHT) vessel has been designed and constructed to facilitate this critical measurement of the silicon MEMS element directly through a process of mechanically “floating” the silicon MEMS element while being subjected to the extreme environments of pressure and temperature, simultaneously. Furthermore, the HPHT vessel is scalable to permit up to fifty specimens to be tested at one time to provide a statistically significant data population on which to draw reasonable conclusions on long-term stability.

With the knowledge gained on the silicon MEMS element, higher level assembly to the pressure transducer envelope package can also be quantified as to the build-effects contribution to long-term stability in the same HPHT vessel due to its accommodating size.

Accordingly, a HPHT vessel offering multiple levels of configurability and robustness in data measurement is presented, along with 20 year long-term stability results.

9061-145

Design of active whole-spacecraft vibration isolation based on voice-coil motor

Weichao Chi, Dengqing Cao, Harbin Institute of Technology (China)

The satellite carries many kinds of precision payloads which require a stable environment to prevent them from being damaged in the process of launching, and isolation systems between the launch vehicle and the satellite has been put in study in the past decades. The active approach can provide a suitable force which is depend on the sensor's feedback to reduce the amplitude of the vibration. In some cases, the active approach may has a better performance at resonance frequencies and allow for a more simple structure to get the same effect compared with the passive approach.

As an active vibration system, there must be an actuator which could provide the force to work against the disturbance. Voice coil motor (VCM) is a device which converts electric energy into mechanical energy. As a kind of direct motor, voice coil actuator has many good features, such as high linearity, high sensitivity, it can generate force with high accuracy and acceleration over a sufficient range of movement.

This paper focused on whole-spacecraft vibration isolation platform with eight active struts. The isolator was designed to isolate the vibration in the range from 10 to 1000Hz in six DOF. A VCM was designed and optimized as the actuator so that it could provide enough feedback force and was fixed in a whole-spacecraft vibration isolation platform, with sensors collocated on one side of the VCM in the vertical direction. Integral force feedback control law and acceleration feedback control law was designed and compared by numerical simulation and experiment.

9061-146

An FFT-based approach for dynamic response prediction of non-periodic systems

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The definition of an accurate model representing the dynamic behavior of real systems has a significant impact on the understanding of mechanical aspects of the system. Due to lack of information on the physical properties as well as complexity of applied loading, accurate modeling is not usually a simple task. In this work, a combined experimental and numerical approach, called Extended Load Confluence Algorithm (ELCA), is presented to improve the accuracy in the modeling of the dynamics of a structural system through an updating iterative approach, in order to achieve a satisfying level of accuracy in terms of displacements, strains, and accelerations. ELCA is based on a numerical model for prediction of the system's behavior through a few iterations and takes advantage of modal expansion to reconstruct the full-field dynamic response from a limited set of experimental data. The algorithm starts with an initial guess of the applied loads and updates them at each iteration in order to match the numerical dynamic response with the experimental measurements at the sensors locations. The algorithm is formulated in the frequency domain with the use of a Discrete Fourier Transform (DFT). The paper will describe numerical cases that demonstrate that a few sensors are sufficient to represent the overall behavior of the system in just a few iterations. Moreover, experimental validation on a one-dimensional structure will show the effectiveness of proposed approach. The convenience of proposed approach can be considerably beneficial when applying for structures with complex loading conditions in aerospace and mechanical applications.

9061-147

Scanning Capability Analysis of Laser Impulse Radar

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Abstract: The reflector of inflatable antenna is made of flexible membrane and it is unlike solid antenna for controlling of accuracy. Pressure is one of the important measures to control surface accuracy of inflatable antenna. The purpose of the study is to highlight the effect of pressure on accuracy by experiment and numerical analysis. 25m Ka-Band Inflatable/Self-Rigidizable Reflect Antenna is researched. The research work investigated the effect using rapid, contactless, and low-cost digital photogrammetry system(DPS) according to its lightweight and flexible characteristics. Data shows that the best pressure and the best area in this pressure can be obtained by measurement. Numerical analysis was run in order to check the measurement result. By contrast, there is of a little difference between them. The difference is attributed to wrinkle. The results of analysis and test show that surface accuracy of the reflector can be adjusted by controlling pressure.

9061-148

Nanomaterial based sensor for monitoring real time aging process in structural composites

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The unpredictable aging process in composites is one of the main problems that limit its use for many structural applications. In this study, a nanomaterial based sensor technology that can provide wide area detection of composite degradation and damage was used. The CNT grown on (fuzzy fiber) sensors exhibit similar sensitivity to conventional strain gages and are more easily integrated into composite structures as the sensor itself is a composite. Fuzzy fiber has potential not only of being used as reinforcement but for real time structural health monitoring of the structural system. This could give an indication of an instantaneous behavior of the material condition and specific activity taking place with respect to time during aging process of the composites as well as offers tool in studying the interfacial mechanics of composites. Study was focused on the characterizations and change in the electrical properties (Resistance and capacitance as a function of time, Temperature, and oxidation rate) of fuzzy fiber as a self-sensing technique to monitor process of thermo-oxidative degradation for prognostic analysis of aging in composites. The embedded fuzzy fiber was a valuable tool in monitoring the rate of diffusion of each laminate.

9061-149

Parametric study of laser scanner for breathing cracked rotor damage identification

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Frequency Response Function (FRF) based damage detection method is utilized in this paper to identify the breathing cracks on a rotordynamic system in both frequency and time domain. The cracks are considered to be breathing during rotation due to the effect of gravity or imbalance mass. Zero-SIF (Stress Intensity Factor) method is employed to determine the crack closure line of open crack area. It is found that the stiffness reduction induced by a breathing crack is a function of both

crack phase and rotation angle. The dynamical model of system is built based on the Lagrange principle and the assumed mode method while the crack model is based on the fracture mechanics. The steady-state equation of system is constructed via harmonic balance with a laser scanner as output sensor. The laser scanner enables the sufficient outputs from a single sensor by varying the scanning frequency or scanning function. Parametric study is carried out to show how the variation of laser scanning parameters affects the FRF and damage detection. Assuming a cosine function to approximate the nonlinear breathing behavior of cracks, the linear damage identification algorithms for frequency and time domain are established via Least Square and Newton Raphson methods. Finally, the dynamic response of a rotor system with nonlinear breathing cracks is simulated in time domain and the breathing cracks are successfully identified by developed damage detection algorithm.

9061-150

Application of genetic algorithm in position determination of perturbations along a Sagnac Interferometer

Bingjie Wang, Shaohua Pi, Fudan Univ. (China)

Sagnac interferometric optical fiber sensors are well known for detecting perturbations such as strain, temperature, rotation and vibration on civil structure and mechanical systems due to the merits of low noise, low requirements and high reliability in distributed intrusion sensing system. In such applications, perturbations cause a phase shift to the propagating light on fiber and then the phase shift is modulated to a variation on the output power of light. The position determination of perturbations can be made by null frequencies when analyzing the Fast Fourier Transform spectrum of signal. Therefore, the key of system performance is to determine the null frequencies as exactly as possible. However, it is usually difficult to precisely capture the null frequencies because the spectrum always contains impurity peaks and non-stationary noises. In the previous works, there are no in-depth studies on obtaining null frequency values, sometimes get null frequency values directly read in graphics, which lead to 200m erroneous results, or simply provides simple operations. This work adopts genetic algorithm to determine the accuracy position of null frequencies based on the wavelet analysis results. Genetic algorithm (GA) is a kind of random search and optimization method built on the biological natural selection and genetic mechanism. Experiment results show that we can gain good accuracy of the null frequencies on the frequency spectrum with only 60m errors. The repeatable results indicate that this method is an effective way to accurately locate the position of perturbations along a Sagnac interferometer.

9061-151

Detecting and locating intrusion along a high sensitivity linear Sagnac interferometer

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Distributed Fiber optical sensor has been widely used in communication cables and pipelines defense. Among them, Fiber Sagnac Interferometer shows several merits such as low noise, low requirement and high reliability. While the loop-based configurations are difficult in practical application for two aspects: the inconvenience to install Sagnac loop along a line (such as communication cables) and the isolation of the unused half of the Sagnac loop. Though some linear structures with delay loops or dual-loop were developed to satisfy reality requirements, they usually make a sacrifice of sensitivity and have complex circuits. To acquire high sensitivity with simple circuits, we propose a structure in which the two sides of Sagnac loop are in one cable. When a disturbance applies to the cable, one fiber is compressed and another is stretched, and vice versa. The phases of clockwise (CW) light and the counter clockwise (CCW) light are affected by the disturbance at the same time but with different direction. It means that the phase affection acting on the two fibers by the intrusion are synchronous but differ with half period. Besides the advantages of linear laying and high sensitivity, the high order of null frequencies are integer multiple of the fundamental null frequency. Closer null frequencies make more accuracy on peaks location on the Fourier transform. Experiments on simulating the intrusion in lab have been launched. A 50m resolution has been achieved when the intrusion distance is 100km. This structure is proved simple and accurate.

9061-153

Feature analysis of temperature gradient effect on indirect and direct bridge SHM

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One of the main problems of vibration based bridge structural health monitoring is ambient variations. Variation of the bridge's dynamic characteristics (i.e. fundamental frequency and critical damping) due to environmental conditions has been reported to be greater than the variation caused by severe damage effects. To determine health of the structure, we study the evolution of the feature space under different temperature scenarios.

Including a controlled vehicle, a bridge structure and the supporting structures, an experimental setup that gathers acceleration signals from both a travelling vehicle and a bridge structure was constructed. Both the vehicle and the bridge were equipped with accelerometers, and the signals from each are compared. We refer to direct monitoring as when using the acceleration signals from the bridge and indirect monitoring when using the acceleration signals from the vehicle.

Eleven different temperature scenarios were defined. Each temperature gradient scenario includes one pristine condition and the other three damaged scenarios: concentrated additional mass, additional damping, and partial rotational restraint of one of the supports.

A two-layer classification system is proposed: the first layer classifies the temperature scenarios and feeds the estimated temperature to the second layer; the second layer classifies the different bridge scenarios at each estimated temperature. Since the two-layer classification system splits the influences from temperatures and the bridge scenarios, each factor can be analyzed individually. Local fisher discriminant analysis is used as the feature extractor and support vector machine is used as the classifier in both layers.

9061-154

Application of wavelet domain in identifying vehicular axles in prescreening heavy vehicles

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The significantly increased truck volumes and weights in the past and coming decades poses a challenge to engineers in their maintenance on road infrastructure. It is known that the deterioration of these infrastructure systems is considerably caused by overweight trucks. Bridge weigh-in-motion (BWIM) system are developed to be a promising method for overweight truck enforcement. This paper introduces a recently-developed BWIM, which applied transducers mounted under the bridge of each lane of interest to provide vehicle silhouette and velocity. The BWIM system replaces those conventional BWIM systems who require two axle or vehicle detectors (pneumatic tubes or tape switches)

installed on the pavement. Field tests demonstrate that the collected signals from these transducers sometimes are difficult to clearly identify the axle numbers and thus axle spacings. To improve the efficiency and accuracy in its identification of vehicle axles, this paper presents a wavelet-based analysis of stain signals and shows the efficacy of using wavelets in pattern recognition of these signals. The transformed signals are used to identify axle passage and hence the vehicle velocity and the axle spacing. The wavelet-based algorithm was verified by the field tests with 2- or 3-axle rigid calibration trucks of known weight and axle spacing across the instrumented bridge along different lanes with repeated runs. Field tests demonstrate that the wavelet domain analysis can effectively improve the efficiency and accuracy in identifying vehicle velocity, axle numbers and spacing. The combination of the wavelet-based technology provides promising potential for the successful application of BWIM system on overweight vehicles enforcement.

9061-155

Galfenol-based directional magnetostrictive transducer for guided wave techniques

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Galfenol, an alloy of iron-gallium, is one of high interested magnetostrictive materials due to its capability of transducer development. The galfenol exhibits high magnetostriction, high permeability, and useful thermo-mechanical properties. Also, the galfenol possesses better mechanical properties than most smart materials such as piezoelectric materials, shape memory alloys, and electroactive materials. Such galfenol materials have been applied for vibration-based energy harvesting, active shape and vibration control, and Structural Health Monitoring (SHM) applications.

In order for Non-Destructive Evaluation (NDE) of structures, magnetostrictive transducers made of ferromagnetic materials such as Ni or FeCo strips/patches and magnetic circuits have been developed and successfully applied for SHM of pipes, plates, bridge cables, and tubes. The magnetostrictive transducers are based on direct and inverse magnetostrictive effect to generate and detect the Guided Waves (GWs), respectively, propagating within structures. In general, magnetostrictive strips/patches are permanently bonded onto the host structures, and permanent magnets and solenoid coils are used to generate magnetic fields over the magnetostrictive materials and sense strain-induced magnetic field change.

In this study, single-crystal galfenol patches are used to develop directional magnetostrictive transducer for GW-based SHM of plate-like structures. The galfenol possesses much larger magnetostriction than common ferromagnetic materials, which means the galfenol-based magnetostrictive transducers provide a high actuation and sensing effect for the GW interrogation techniques. In addition, the single-crystal galfenol has better magnetomechanical sensitivity at the specific crystal orientation direction than polycrystalline galfenol. Using the characteristics of the single-crystal galfenol, the directional magnetostrictive transducers are developed for the GW-based damage detection applications.

9061-157

Remote thermomagnetic sensing for internal temperature mapping of cylindrical lithium-ion batteries

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Remote temperature sensing using thermomagnetic coupling was developed to enable wire-free internal temperature monitoring of cylindrical Li-ion batteries. Two challenges hamper existing multi-point temperature scanning technology: complex wiring for contact based measurements like thermocouples and limited penetration depth for scanning approaches like infrared sensing. In this paper, we present a wireless sensing approach integrated into an operating Li-ion battery to monitor the real-time core temperature variations during charging and discharging cycles. Our approach uses magnetic property changes in a thermomagnetic material (Ni-Cu alloy) targets inserted into a battery core. Low frequency magnetic fields are used to monitor the target's magnetic properties which can be related to temperature through calibration experiments. The external temperature can also be detected by increasing the frequency and using traditional eddy current techniques on the external case of the battery. By dynamically scanning along the axial direction, we were able to deduce the temperature along the axis of the battery. To verify the temperature measurements, we inserted a thermocouple into the core near the thermomagnetic target. Good agreement between thermomagnetic sensing and thermal couple results was obtained with an error of less than 2 oC for both static and dynamic temperature sensing with 1 msec response time and 1 sec full scanning time.

9061-158

Combining computer vision and static sensor information through data fusion

David Lattanzi, George Mason Univ. (United States)

Digital inspection images are complex sources of information and have historically been underutilized for structural monitoring due to a lack of robust analytical methods. However, recent innovations in computer vision enable both the extraction of salient inspection information from 2D images as well as the automatic placement of images within their inherent 3D spatial context. These image analysis methods produce local descriptions of observed damage within an image and cannot inherently correlate the impact of detected damage to the global performance of civil structures.

Concurrently, the last several decades have seen rapid advances in the capabilities of static, accelerometer-based sensor networks and associated monitoring systems. Fundamentally, these systems measure the global dynamic response of a structure and quantify changes to the dynamic response.

Considered together, images and accelerometers are complementary sources of structural monitoring information capable of describing both local phenomenon and the associated global response. Developed herein is a methodology for integrating image and accelerometer information using a combination of computer vision and data fusion techniques. The challenges associated with such an integration include: (i) developing robust descriptions of image-based damage information, (ii) calculating the spatial context of damage detected in images, and (iii) creating a data fusion method capable of integrating disparate sources of health monitoring information.

9061-159

Implementation of a self-sensing piezoelectric actuator for vibro-acoustic active control

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Significant reduction of airplane interior noise may be obtained by active structural acoustic control (ASAC) of fuselage panels. This requires to accurately measure the vibrations of the aircraft panels while injecting anti-vibrations. Co-located piezoelectric sensors and actuators, spatially

distributed on the structure, are an interesting avenue since they can lead to the implementation of distributed virtual impedances. When the same piezoelectric device is used to simultaneously measure and actuate, it is called a self-sensing piezoelectric actuator (SSPA).

When a SSPA is submitted to a voltage, the measured current is the sum of the electric current due to the capacitive effect of the transducer plus the mechanical current induced by the strain of the structure. The latter is an order of magnitude smaller than the total current measured. Provided the measured current is digitized with sufficient accuracy, adequate numerical processing can subtract the capacitive current from the total measured current. A similar processing can also be used to subtract from the sensor information, near-field vibrations induced by the collocated actuator. Hence, information related to the global, vibrational flexural modes of the plate is extracted without complicated electronics.

The numerical method of current separation has been programmed and validated with Matlab/Simulink and implemented on an Opal-RT system. A shunt resistor is used to measure the current simultaneously with the voltage measurement. Strain-induced current has been successfully extracted from SSPA signal with this method. Numerical simulations show good agreement with experimental data.

9061-162

Bio-inspired flow sensors using carbon nanomaterials

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Fish utilize neuromasts to help them detect changes in water flow, which is essential for swimming, tracking prey, and performing synchronized swimming maneuvers. The neuromasts contain a staircase of hair cells that perform this task by transforming mechanical stimulation from the flowing water to electrical impulses that ultimately are transported to the brain. Inspired by the physical structure of the hairs, flow sensors are fabricated using carbonaceous nanomaterials partially embedded in a polydimethylsiloxan (PDMS) polymer substrate, which leaves part of the nanomaterial exposed to the fluid flow. This is an effective means of sensor fabrication that prevents the carbon nanomaterial from being washed away by the flowing liquid. Different carbon materials such as long and short single walled carbon nanotubes, carbon nanohorns, peapods, and multi walled carbon nanotubes are investigated in this research. All sensors from these carbon materials performed well when fabricated using this method. Future focus of this research will be to maximize electrical response by implementing different techniques, aimed at improving hydrophilicity by introducing a functional group such as siloxane (SiOH) to the sensing surface and increasing the surface area in contact between the electrodes and the sensing surface.

9061-163

A robotic reproduction of the dynamic sonar sensing in horseshoe bats

Brandon Goodman, Rebecca Castro, Yanqing Fu, Rolf Mueller, Michael K. Philen, Virginia Polytechnic Institute and State Univ. (United States)

Horseshoe bats (family Rhinolophidae) are a group of bats with a particularly sophisticated biosonar system that allows them to navigate and pursue prey in dense forest habitats. One conspicuous feature of horseshoe bat biosonar is that the pulses are emitted nasally and diffracted by a special baffle structure - the noseleaf - as the exit into the free field. Furthermore, the noseleaves can change their shapes while diffracting the outgoing ultrasonic waves. The aim of this research project is to obtain experimental data on how the deformation of the noseleaf during pulse emission affects the ultrasonic field. An automated experimental setup approach was used to achieve this aim. The experiment setup was designed and integrated the acoustic instruments for emitting the pulses and recording the signal, such as ultrasonic loudspeaker and high sensitive actuators for displacing the noseleaf and orienting the noseleaf, such as linear actuator and pan and tilt unit. A cone and tube waveguide was designed to match the loudspeaker to the nostrils. By using this experimental system, it is possible to reproduce the dynamic effect of the noseleaf and characterize it as a basis for inspired dynamic acoustic devices. Future research is to determine which deformations of the noseleaf affect the acoustic field.

9061-164

Study the selecting of structural characteristic responses for finite element model updating of structures

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The field measurements of structures are very important to the structural finite element (FE) model updating because the errors and uncertainties of a FE model are corrected directly through closing the discrepancies between the analytical responses from FE model and the measurements from field testing of a structure. Usually, the accurate and reliable field measurements are very limited. Therefore, it is very important to make full use of the limited and valuable field measurements in structural model updating to achieve a best result with the lowest cost. In this paper, structural FE model updating is investigated in the point of view of solving a mathematical problem, and different amount and category of structural dynamic responses and static responses are considered as constraints to explore their effects on the updated results of different degree and types of structural damages. The numerical studies are carried out on a space truss. Accounting for the numerical results, some inherent phenomena and connections taking account of the updating parameters, output responses and the updated results are revealed and discussed. Some useful and practicable suggestions about using the field measurements for FE model updating are provided to achieve efficient and reliable results.

9061-165

Detection and calculation of reflected spectral shifts in Fiber-Bragg gratings (FBG) in polarization maintaining optical fiber

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Fiber-Bragg Gratings (FBG) for Structural Health Monitoring (SHM) have been studied extensively as they offer electrically passive operation, EMI immunity, high sensitivity, and multiple multiplexing schemes, as compared to conventional electricity based strain sensors. FBG sensors written in Polarization Maintaining (PM) optical fiber offer an additional dimension of strain measurement simplifying sensor implementation within a structure. This simplification however, adds complexity to the detection of the sensor's optical response to its corresponding applied strain. We propose a method that calculates spectral shifts caused by axial and traversal strains for PM FBG sensors. The system isolates the orthogonal propagating optical waves incident to the optical interrogators. The post-processing algorithm determines the wavelength shifts, compares to a predetermined baseline then correlates the shift magnitudes to a respective strain. Two initial experiments are performed: The quantification of spectral reflection shifts via random spectral shifts of a coherent baseline signal and the calibration of a Single Mode (SM) FBG sensor on a composite sample. These exercises validate the method of optical detection and shift calculation of multi-axis sensors as an integrated system.

9061-166

A statistical learning method for damage identification with guided-wave sensors in composites

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This study proposes a new statistical approach for damage identification with guided-wave sensors.

A model updating strategy is employed to improve the damage prediction capability of a finite element analysis (FEA) model with experimental observations from a Lamb-wave sensing system. The approach statistically calibrates unknown parameters of the FEA model and estimates a bias correcting function to achieve a good match between the model predictions and sensor observations. An experimental study is presented in which a set of controlled damages are generated on a composite panel. Time-series signals are collected with the damage condition using a Lamb-wave sensing system and a one dimensional FEA model of the panel is constructed to quantify the damages. The damage indices from both the experiments and the computational model are used to calibrate assumed parameters of the FEA model and to estimate a bias-correction function. The updated model is used to predict the size (extent) and location of damage. It is shown that the proposed model updating approach achieves a prediction accuracy that is superior to a purely statistical approach or a deterministic model calibration approach.

9061-62a

Measurement of Kirchhoff's stress intensity factors in bending plates

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A measurement method of the stress intensity factors defined by KIRCHHOFF's theory for a crack in a bending plate is shown. For this, a thin piezoelectric polyvinylidene fluoride film (PVDF) is attached to the surface of the cracked plate. Measured electrical voltages are coupled with the load type and the crack tip position relative to the sensor film. Stress intensity factors and the crack tip position can be determined by solving the non-linear invers problem based on the measured signals. To guarantee solvability of the problem, more measuring electrodes on the film have to be taken in to account. For the developed sensor concept the KIRCHHOFF's plate theory is assumed. In order to connect the electrical signals and the stress intensity factors the stresses near crack tip have to be written in eigenfunctions (see WILLIAMS [1]). The presented method was verified on the example of a straight crack of the length 2a in an infinite isotropic plate under all side bending. It was found that the positioning of the electrodes is delimited by two radii. On one hand, measurement points should not be too close to the crack tip. In this area, the Kirchhoff's plate theory cannot be used effectively. On the other hand, the measuring electrodes should be placed with a smaller distance to each and not too far from the crack tip regarding of the convergence radius of the WILLIAMS series expansion. Test calculations on straight crack in an infinite isotropic plate showed the general applicability of the measurement method.

[1] WILLIAMS, M., L., "The bending stress distribution at the base of a stationary crack", Journal of Applied Mechanics, 28, 78-82 (1961)

9061-63a

Crack detection sensor layout and bus configuration analysis

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In crack detection applications large sensor arrays are often needed to be able to detect and locate cracks in structures. This paper analyzes different sensor shapes and layouts to determine the layout which provides the optimal performance. A "snaked hexagon" layout is proposed as the optimal sensor layout when both crack detection and crack location parameters are considered.

In previous work we have developed a crack detection circuit which reduces the number of channels of the system by placing several sensors onto a common bus line. This helps reduce data and power consumption requirements but reduces the robustness of the system by creating the possibility of losing sensing in several sensors by a single broken wire. In this paper, sensor bus configurations are analyzed to increase the robustness of the bused sensor system. Results show that spacing sensors in the same bus out as much as possible increases the robustness of the system and that at least 3 buses are needed to prevent large segments of a structure from losing sensing in the event of a bus failure.

9061-64b

Detection of functional states of a resident using sensor agent robot

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Smart house, one of human-centered systems, has been studied for satisfying various needs of residents. However, they do not respond to unexpected disturbances, aging of residents and buildings, and dynamic changes of human emotions. Considering this fact, we suggest "Biofied Building" to resolve the problems by applying adaptation mechanisms of living things. In Biofied Building, to get information about human and environment of building is the most fundamental function. Because there is various information in living spaces, we referred ICF(International Classification of Functioning) which is offered by WHO to determine which information we should get. The ICF includes all living functions of human in living spaces. Thus we can categorize all kinds of information about a human by detecting each state of living functions. In this study, we focus on walking patterns which are external states of living functions of a human. It is indicated that changes of gait such as decline of walking speed will result in more frequent fall and onset of cognitive impairment. In other words, detecting external states such as some parameters about walking patterns can prevent some disease of a resident. In this paper, we propose a new system that measures some parameters about walking patterns using a sensor agent robot routinely in buildings. We use the sensor agent robot, called e-bio, which is equipped with Kinect. The sensor agent robot follows the human's walking and detects walking parameters simultaneously. The experimental results showed that we can obtain high-precision walking information using the proposed system.

9061-65b

A novel human-machine interface for communicating the orientation of multicopters to human operators

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Multicopters can enhance the development of technical projects in

several fields because of their stable flight characteristics and simplicity of construction. The control of a quadcopter is based on the knowledge of several variables such as velocity, position and orientation. During manual or pilot-supported autonomous flight, the pilot must control all these parameters simultaneously. It has been found difficult for human operators to visually estimate the orientation of the multicopter at any given time while controlling the vehicle. Since the pilot must simultaneously be aware of so many multicopter parameters during operations, we propose a novel vibro-haptic human-machine interface to communicate state information to the human operator. The hope is that by utilizing a vibro-haptic display, additional information can be communicated to the human operator without consuming valuable visual and auditory bandwidth normally required to control the multicopter. A vibro-haptic solution based on an instrumented belt wirelessly communicated to a simulated multicopter's compass is investigated in this work. Through this new application, the pilot receives tactile stimulus with every quadcopter's orientation change, so that it is no longer necessary to visually estimate the orientation of the multicopter during operation.

9061-66a

Dynamic interrogation of passive wireless antenna sensor

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In our previous work, we have demonstrated that the resonant frequency of a patch antenna is highly sensitive to its dimension changes and thus can be used for mechanical strain sensing. However, the wireless interrogation scheme developed so far is too slow for vibration measurement1-3. This paper presents a dynamic interrogation approach using the FMCW technology. The wider frequency sweeping range (1GHz) and the higher interrogation rate (up to 50Hz) of the FMCW interrogation signal makes real-time vibration measurement using the patch antenna sensor possible. The FMCW interrogation signal is generated by controlling a voltage control oscillator (VCO) using a linear ramp signal. An amplitude modulation circuit is implemented at the sensor node to shift the sensor signal by a given modulation frequency and thus separate the sensor signal from the interrogation signal backscattered by surrounding structures. The wirelessly received sensor signal is demodulated at the wireless interrogator using a down-conversion mixer and a band-pass filter. An envelope detector circuit was designed and implemented to produce an analog signal that is proportional to the amplitude of the demodulated antenna signal. Finally, LabView and MATLAB programs are developed to perform continuous data acquisition and digital signal processing. The design, implementation, and characterization of this dynamic wireless interrogation system will be discussed.

9061-67a

Quasi-static self-powered sensing and data logging

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Many signals of interest in the assessment of structural and physical systems lie in the quasi-static range (frequency << 1Hz). This poses a challenge for the development of self-powered sensors that are required to monitor these events and also to harvest the energy for sensing, computation and storage from the signal being monitored. This paper combines the use of mechanically-equivalent energy comparators and concentrators with analog floating-gate sensing modules capable of computation and data storage with total current less than 10nA. The combined multi-stage energy concentration, transduction, and sensing allows the self-powered monitoring of extremely low-rate cyclic events including, but not limited to: temperature and pressure fluctuations, and low rate mechanical deformations.

The used mechanically-equivalent comparators and energy concentrators allow the transformation of the low-amplitude and low-rate quasi-static variations into an amplified input to a piezoelectric transducer. The sudden transitions in unstable mode branch switching, during the elastic postbuckling response of slender columns and plates, are used to concentrate the distributed energy over long periods into high amplitude energy bursts. This significantly minimizes leakages in the sensing circuits.

In this work, we show that a linear injection response of our combined frequency converter / piezo-floating-gate sensing system can be used for self-powered monitoring of quasi-static deformations at frequencies ranging from 1Hz to as low as 0.005Hz.. The experimental results demonstrate that a sensor fabricated in a 0.5-?m CMOS technology can count and record the number of quasi-static input events while operating at a power levels lower than 1µW.

9061-68a

Compressive sensing based wireless sensor for structural health monitoring

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Lossy wireless communication is a common problem for monitoring systems based on wireless sensors. Reliable communication service, which enhances communication reliability by repetively transmitting unreceived packets, is one approach to takle the problem of data loss. An alternative approach, however, allows data loss to some extent and attempts to recover the lost data from an algorithmic point of view. CS provides such a data loss recovery technique. This technique can be embeded into a smart wireless sensor platform and effectively increases wireless communication reliability without re-transmitting the data. The basic idea of CS-based approach is that, instead of transmitting the raw signal acquired by the sensor, a transformed signal which is created by projecting the raw signal onto a random matrix, is transmitted. Some data loss may happen during the transmission of this transformed signal. However, according to the theory of CS, the raw signal can be effectly reconstructed from the imcomplete transformed signal given that the raw signal is compressible in some basis. This technique has been embeded into Imote2 smart sensor platform and tested in a series of experimentis. Also the field test of bridge is carried out to illustrate the performance of the approah. The reults show that the CS based Imote 2 can attack the data loss problem by reconstructing the lost data avoiding re-requesting to re-send data agian and the continuous data acquisition can be achieved.

9061-69a

Development of an extensible dual-core wireless sensing node for intelligent infrastructure monitoring and controls

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Wireless telemetry has been successfully introduced into the structural monitoring and controls field for cost-effective deployment in operational civil engineering systems. While great advances have been made, prior wireless sensor nodes have focused on a single-core microprocessor cores that are challenged when the node is required to multi-task its operation. In this study, a novel approach to the design of wireless sensors based on dual-core microprocessors is introduced for explicit multi-tasking operations including concurrent execution of monitoring and controls. The Martlet is an extensible platform for executing computationally complex control and signal processing algorithms within a wireless network. Built around the Texas Instruments TMS320F28069 digital signal processing microcontroller, the Martlet features an auxiliary computational core for true parallel execution of time critical algorithms alongside necessary overhead computations. Connectors on the top and bottom link all the features of the micro-controller to an array of peripheral boards, a.k.a. 'Martlet Wings', enabling nearly any sensor, actuator, or power harvesting device to interface with the Martlet. Example applications include feedback control of: semi-active vibration control devices, HVAC systems, industrial processes, and large scale civil infrastructure. In this study, a network of Martlet nodes is installed on an operational wind turbine for validation of the system performance for continuous vibration monitoring.

9061-70a

Integrated wireless sensor network and real time smart controlling and monitoring system for efficient energy management in standalone photovoltaic systems

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In the last decade, the integration of wireless sensors in energy management systems enhances the performance of these systems. For renewable energy systems, the integration of wireless sensors in monitoring and management is more essential and more complicated due to the increasing number of parameters and variables which have to be considered. This makes the development of a reliable wireless energy monitoring and management system which is able to efficiently characterize the operation and optimize the performance of renewable energy system with minimum cost and best quality a must. The previous goals are steadily achieved by the continuous research efforts to develop more efficient data monitoring and management systems and to improve the capabilities of wired and wireless communication network. The recent developments in wireless sensor network technologies, the intranet and internet topologies, and the rapid developments of computational facilities are opening the ways to design and implement efficient real time wireless energy monitoring and management for renewable energy systems.

In the present work, wireless sensor network and smart real-time controlling and monitoring system are integrated for efficient energy management for standalone photovoltaic system is designed and implemented. Our proposed system is designed to have the ability to extend the number of monitored quantities to accurately describe the status of renewable energy system through real time monitoring. The main functions of our proposed system is to efficiently control the energy consumption form the PV module based on accurate determination of the periods of times at which the loads are required to be operated and to monitor the performance of the system of by continuous calculating and recording of the consumed and generated power from the PV system. These requirements are fully fulfilled using an accurate and efficient real time monitoring and controlling system which is continuously fed with updated input data from the wireless sensors and send controlling signals wirelessly to the loads. It has to be mentioned that our proposed system is flexible to be upgraded to fulfill additional users' requirements

9061-35b

Lithographically patterned carbon nanotube thin films for distributed strain sensing

Jerome P. Lynch, Andrew Burton, Univ. of Michigan (United States); Masahiro Kurata, Kyoto Univ. (Japan)

Engineers today are faced with the challenges of both maintaining aging infrastructure and advancing the performance of future structural systems. These pursuits require the implementation of emerging materials and engineering capabilities such as micro-scale processes and nano-engineered materials to realize previously unattainable intelligent system performance through advanced sensing capabilities. There have been numerous such recent efforts toward improved structural sensors through the implementation of exceptional mechanical and electrical properties displayed by carbon nanotubes (CNTs). Many of these efforts displayed promising possibilities in sensing structural damage through the electrical response of CNT-polymer composite thin films. However, an efficient, scalable method for creating CNT thin film sensors is yet to be realized. We seek to transcend current limitations in CNT thin film fabrication and transduction by employing MEMS fabrication processes to create patterned CNT films that will allow for greater fabrication scalability and exceptional signal resolution for sensing distributed strain. This study investigates the use of patterned CNT-polymer composite thin films for the realization of efficient damage detection with exceptional spatial resolution on the scale required by our built infrastructure. These sensors were realized through repeatable lithographic processes commonly used in the creation of microelectromechanical systems (MEMS). Thin film sensing specimens were deposited on glass substrates with patterns optimized for measuring the strain response of welded steel connections. Validation of the patterned CNT-polymer thin film sensors is conducted using a partial-scale beam-column steel connection tested under dynamic and quasi-static loads.

9061-71b

Alignment and dispersion of functionalized carbon nanotubes in carbon fiber composites for enhanced sensing capabilities

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Due to their combination of mechanical, electrical and thermal properties, carbon nanotubes (CNTs) show great potential for the development of next generation advanced composite materials. Besides the improved properties in CNT based nanocomposites, additional sensing capabilities have been investigated for detecting structural damage. This paper will focus on the enhanced sensing capabilities by aligning functionalized CNTs using electric field. The effects of both DC and AC electric fields on CNT alignment will be studied. An improved CNT orientation will be examined using polarized Raman spectroscopy, Fourier transform infrared spectroscopy, and field emission scanning electron microscope. The aligned CNTs will be integrated within carbon fiber reinforced composites to understand their damage detection and sensing capabilities, especially for progressive damage and damage precursor. The piezoresistance based sensing capabilities of aligned CNTs will be compared with those of randomly dispersed CNTs. The damage detection capabilities will be experimentally studied using different types composites coupons including single lapped share joints and stiffened T joints.

9061-72b

Strain paint: non-contact strain measurement using single-walled carbon nanotube composite coatings

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Strain measurements are essential in structural health monitoring. Traditional strain gages require physical contact between the sensor and read-out device, perturb the surface being monitored, and allow measurement only at the specific location and orientation axis of the sensor. We demonstrate a novel non-contact, multi-point, multi-directional strain sensing approach that overcomes these limitations. In our method, the surface is coated with a thin film of “strain paint” containing individualized single-walled carbon nanotubes in a polymeric host. After curing, substrate strains are transmitted through the polymer film to embedded nanotubes. This induces axial strains in the nanotubes, systematically shifting the wavelengths of their characteristic near-infrared fluorescence peaks. To measure strain, a visible laser excites nanotubes at points of interest on the surface, and the near-infrared emission is collected and spectrally analyzed. Observed spectral shifts reveal quantitative strain values. Laboratory tests show sensitivity down to ~400 ??, limited by mechanical properties of the polymeric host film. We also vary excitation beam polarization to find the axis of substrate strain. Our method provides spatial resolution down to its gage length of ~100 ?m. Because the entire substrate is coated with nanoscale strain sensors, measurements can be made at arbitrary locations to construct a full strain map. We will describe recent strain paint refinements involving selection of polymer host, nanotube surfactant, nanotube dispersion method, and preparation protocol. Finally, we characterize the orientational distribution of nanotubes using a probabilistic model combined with experimental data.

Reference: P. A. Withey, V. S. M. Vemuru, S. M. Bachilo, S. Nagarajaiah, and R. B. Weisman, Nano Letters 12, 3497-3500 (2012).

9061-73b

The importance of interfacial resistance on the thermal behavior of CNF/epoxy composites

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This research addresses the thermal transport in carbon nanofiber (CNF)/epoxy composites via finite element modeling. The effects of nanofiber orientation on thermal transport are investigated through simulation of the laser flash experiment technique and through Fourier’s Law of heat conduction. The effects of CNF volume fraction and magnitude of thermal interface conductance on the effective composite thermal conductivity are also quantified. It was found that the interface thermal resistance can significantly alter the heat flow within the nanocomposite, with respect to a resistance-free ideal case. In addition, interface resistance leads to heat entrapment near the interface close to the heat source, which can promote interface thermal degradation. The results of this research address the significance of engineering the interfacial resistance in order to tailor the thermal conductivity of these composites and also the tailoring of thermal transport.

9061-74b

Fabrication of single-walled carbon nanotube sensor arrays by laser-induced forward transfer

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Precise positioning of different active compounds with micro and even nano scale resolution over large areas is the main demand in the development of next generation research applications such as sensors and microarray chip devices. Laser-induced forward transfer (LIFT) has emerged as a powerful technique for printing a wide range of materials in solid or liquid phase. In LIFT, a laser beam is focused through a transparent plate onto the backside of a photodegradable triazene polymer (TP) thin film coated with the material to be transferred (donor film). The TP acts as a dynamic release layer and also protects the material to be transferred from direct laser irradiation. Each laser pulse promotes the transfer of the thin film material onto a receiver substrate that is placed parallel and facing the thin film. The donor-receiver system is placed on a xyz stage allowing the fabrication of well-defined 2D and 3D patterns.

The objective of this work is the application of LIFT for the fabrication of chemiresistor sensor arrays. The receiver substrates contain an array of metal electrodes deposited onto flexible and rigid supports. The active materials placed by LIFT are single walled carbon nanotubes (SWCNT). First the process parameters for printing functional pixels of SWCNT i.e. conducting pixels onto the sensor electrodes are investigated. Second, the sensor arrays are characterized in terms of their sensing characteristics, i.e. sensing of different volatile organic compounds such as ammonia, acetone, methanol, etc. proving the feasibility of LIFT for the fabrication of cheap SWCNT sensor arrays.

9061-76a

Optical fibre Raman spectroscopy: a potential system for monitoring the durability of concrete structures

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Infrastructure represents about 50% of the national wealth. With the majority of the infrastructures being constructed with concrete, the importance of real-time in situ monitoring and thereby timely repair of concrete structures cannot be over-emphasized. Although various sensor systems have been developed for concrete structures, most of them only can monitor the physical changes, i.e. the consequence after the deterioration mechanisms have already been formed. To predict the service life and, especially, to accurately diagnose the causes of the deterioration, the change of the internal chemistry of concrete, not just only the physical properties, must be monitored.

The previous study reported by the authors indicated that, with an ‘optical fibre excitation + spectroscopy objective collection’ Raman spectroscopy configuration, the deterioration mechanisms of sulfate attack was successfully identified. In the current study, a tailored ‘all-fibre’ Raman spectroscopy under a ‘fibre excitation + fibre collection’ configuration was developed on the principle of the coaxial design and classic backscattering geometry to monitor the sulfate and carbonation mechanisms. Bench-mounted Raman spectroscopy and X-Ray diffraction (XRD) analysis were also conducted to verify the results obtained. The main carbonation products, i.e. calcite and aragonite, and the main sulfate attack products, i.e. ettringite and gypsum, were

successfully identified by the ‘all-fibre’ Raman spectroscopy. The results were also verified favourably by the Bench-mounted Raman spectroscopy and XRD analysis. Based on the results obtained, the potential and the challenges for developing a Raman spectroscopy based optical fibre sensor system for in situ monitoring of concrete durability are also discussed.

9061-77a

Fiber optic sensing system for in-situ simultaneous monitoring of water stage, quality, and temperature

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To accurately track the water stage changes and environmental influences on water quality and have sufficient follow-ups to prevent potential flood and environmental hazards, an in-situ continuous monitoring system for water stage and quality is helpful. Traditional in-situ water-stage monitoring system has relative low accuracy and require separate sensors for water quality and temperature which complex the evaluation. Advanced optical fiber sensors, with unique features of real-time and multi-parameter sensing capacity, could provide potential simultaneous evaluation of flooding, water-quality deterioration, and science-based decision support. In this study, an in-situ monitoring system for water stage, overall water quality, and temperature is developed using long-period fiber grating (LPFG) sensors. When part of the LPFG sensor is submerged in water, the resonant wavelength of each cladding mode of the LPFG sensor varies linearly with the submerged length (refer to water stage) and temperature, and nonlinearly with refractive index changes (referred to the water quality). Two resonant wavelengths were used to relate the water stage and overall water quality to the change in resonant wavelengths of the LPFG sensor. Sharing the same fiber line, one sequential glass packaged LPFG was used to monitor the temperature changes at the same location. The algorithm for simultaneous determination of the water stage, overall water quality, and temperature was analytically formulated and experimentally validated. Benefit from the multi-parameter sensing using one single fiber line, the developed optical sensing network can potentially provide a low-cost, real-time, and high resolution solution for the in-situ water quality monitoring.

9061-80b

Strain and damage self-sensing cement composites with conductive graphene nanoplatelet

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A novel cement composite containing graphene nanoplatelet (GNP) which can sense its own strain and damage is introduced in this paper. Piezoresistive strain sensing was investigated for mortar specimens with GNP under monotonically increasing compressive and tensile strain. Under compression, the electrical resistance decreased with increasing strain and can be described by a bilinear curve with a kink at about 400 microstrain. At low strain, a high gage factor was measured and this can be attributed to the reducing interfacial distance and forming of better contacts between GNP and cement paste when the composite was initially loaded. This initial slope varies with the volume fraction of GNP and can exceed 103 for 4.8 vol% of GNP. At higher compressive strain, the slope is consistently about 102 for GNP content exceeding the percolation threshold and this is characteristic of the gage factor for this composite. A different response was observed for specimens under tensile strain due to the absence of closure of the interface. The electric resistance rises with increasing tensile strain with a gage factor of about 102 but rises rapidly after crack initiation. Electric potential method (EPM) is explored for damage sensing in this conductive cement composites. Testing results reveals that the high conductivity achieved by adding GNP can minimize the influence of moisture and reduce the noise-to-signal ratio. Closed form expressions for the prediction of crack depth are derived based on the mathematical analogy between the electrostatic field and the elastostatic field under anti-plane shear loading.

9061-81b

The poling of PVDF matrix composites for integrated structural load sensing

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Carbon fiber reinforced composites are widely used in many structures that require high strength and low weight. For the safety and reliability of these designs, the integrity of the structure needs to be monitored through structural health monitoring. The limitation of typical monitoring approaches such as periodic inspections or use of sensors is that only the locations that are checked or equipped with sensors are evaluated for damage. The purpose of this study is to create and evaluate a smart composite structure that can be used for integrated load sensing and structural health monitoring. In this structure, PVDF films are used as the matrix material instead of epoxy resin or other thermoplastics. The reinforcements are two layers of carbon fiber with one layer of Kevlar separating them. Due to the electrical conductivity properties of carbon fiber and the dielectric effect of Kevlar, the structure acts as a capacitor. Furthermore, the piezoelectric properties of the PVDF matrix can be used to monitor the response of the structure under applied loads. In order to exploit the piezoelectric properties of PVDF, the PVDF material must be polarized to align the dipole moments of its crystalline structure. The optimal condition for poling the structure was found by performing a full factorial design of experiment (DOE). The factors that were studied in DOE were temperature, voltage, and duration of poling. Finally, the response of the poled structure was monitored in tensile and compression tests to show the structure’s effectiveness in measuring both types of loads.

9061-82b

Development of microsized slip sensors using dielectric elastomer for incipient slippage

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A humanoid robot hand receives much attention in various fields. In dexterous robot hand, slip detecting tactile sensor is essential to grasping objects safely. Moreover, slip sensor is useful in robotics and prosthetics to improve precise control during manipulation tasks. In this paper, sensor based-human biomimetic structure is fabricated. We reported a resistance tactile sensor that can detect a slip on the surface of sensor structure. The resistance slip sensor that the novel developed uses acrylonitrile-butadiene rubber (NBR) as a dielectric substrate and carbon particle as an electrode material. The presented sensor device in this paper has fingerprint-like structures that are similar with the role of the human’s finger print. We can measure the slip as the structure of sensor makes a deformation and it changes the resistance through forming a new conductive route. To verify effectiveness of the proposed slip detection, experiment using prototype of resistance slip sensor is conducted with an algorithm to detect slip and slip was successfully detected. In this paper, we will discuss the slip detection properties so four sensor and detection principle.

9061-83b

Morphing electro-adhesive interface to manipulate uncooperative objects

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The possibility of handling uncooperative objects, i.e. objects not equipped with any feature that can ease their manipulation, is of particular interest for both terrestrial and space robotic applications.

In this framework, the paper deals with the development and test of a smart material substrate, which can be integrated in an end-effector device, where morphing and electro-adhesive capabilities are combined to allow the manipulation of uncooperative objects of different shapes and materials. Compliance and adhesion properties are obtained creating a conductive pattern of electrodes embodied on the surface of a polymeric substrate. On one hand, the polymeric material, activated by a change in temperature, can adapt to any shape when it is heated, and keep the deformed shape after being cooled, even when the load is removed, becoming compliant with the object surface. On the other hand, the conductive pattern is responsible of the adhesive effect: when a high voltage is applied, the electric field generated induces opposite charges on the object surface establishing reversible attraction forces. Furthermore, the conductive pattern activates the morphing behaviour when the manipulator and the target object get in contact. The development of a test prototype of the conductive polymeric substrate is here presented. Simulations are performed to test both the morphing cycle and the adhesion capabilities in order to determine the power levels required for the polymer activation and the influence of the conductive pattern characteristics on the adhesion forces.

9061-84a

Analyzing the dynamic response of rotating blades in small-scale wind turbines

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The objective of this study was to validate modal analysis and system identification of small-scale rotating wind turbine blades in the laboratory and in the field. In general, wind turbine blades were instrumented with accelerometers and strain gages, and data acquisition was achieved using a prototype wireless sensing system. In the first portion of this study conducted in the laboratory, sensors were installed onto metallic structural elements that were fabricated to be representative of an actual wind blade. In order to control the excitation (rotation of the wind blade), a motor was used to spin the blades at controlled angular velocities. Data measured by the sensors were recorded while the blade was operated at different speeds. On the other hand, the second part of this study utilized a small-scale wind turbine system mounted on the rooftop of a building. Similar to the lab tests, accelerometers and strain gages were installed onto all three blades, and sensor data was relayed via a wireless system. The main difference, as compared to the lab tests, was that the field tests relied on actual wind excitations (as opposed to a controlled motor). The entire system was also more realistic and significantly more representative of other large-scale wind turbine systems. The raw data from both tests were analyzed using signal processing and system identification techniques for deriving the modal response of the blades. The multivariate singular spectrum analysis (MSSA) and covariance-driven stochastic subspace identification method (SSI-COV) were used to identify the dynamic characteristics of the system. The extracted modal properties under different ambient or forced excitations were compared and verified using static test results that were conducted separately. These tests confirmed that dynamic characterization of rotating wind turbines was feasible, and the results will guide future monitoring studies planned for larger-scale systems.

9061-85a

Targeted deployment of scour monitoring sensors for at-risk bridges

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This paper will present the use of stream geomorphic data, bridge design information, and bridge scour ratings to intelligently identify and prioritize sites for remote scour monitoring for bridges in Vermont as a case study. Scour is the leading cause of bridge failure throughout the state and elsewhere. A large number of bridges are rated as scour critical in Vermont. This work looks to correlate bridge structural design data with hydraulic and stream geomorphic information to identify bridges at high risk of scour processes, and specifically for bridges under-designed to resist scour failure. By using stream and hydraulic indicators, rather than relying on structural evaluations alone, areas of geomorphic instability can be identified; and bridges in these areas can be outfitted with scour monitoring devices. This approach can integrate low-cost monitoring devices to monitor at-risk bridges and to provide additional information in areas where scour may occur. A sensor under development would allow for direct installment into stream beds at existing bridges, and incorporate accelerometer based monitoring, with wireless data transmission. The device allows for real-time measurement of degradation and aggradation during high flow events, and alerts the owners to critical scour events. This work is likely to aid state transportation engineers in identifying which bridges in the transportation network are at risk of scour processes, provide useful insight into scour rating systems, and how geomorphic assessments can improve our bridge rating system. Results from geomorphic assessments, scour ratings, lab and field tests will be presented.

9061-86a

On estimating the accuracy of monitoring methods using Bayesian error propagation technique

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From a logical standpoint, structural health monitoring is an inference problem, where we attempt to gain information on the state of a structure based on sensor observations and the expected relationship between observations and state, normally encoded in a mechanical or heuristic model. Wrote in mathematical terms, the estimation of the state variables is formally identical to the metrology problem of indirect measurement, where the measurand is indirectly estimated based on observation of other physical quantities linked to the measurand. In analogy with the metrology problem, in this contribution we use error propagation technique, based on Bayesian logic, to judge a priori the effectiveness of a monitoring method. Particularly we discuss how the heuristic components of the model should be properly accounted and how correlation between observations can be practically handled. We demonstrate the approach on a number of case studies. These include the estimation of the tension of a cable stay based on vibrational measurements. We show how the accuracy of the cable load estimation change based on the estimation technique adopted and how data fusion techniques allow improving its accuracy. We also highlight how the subjective judgment of the individual in charge of the data analysis may affect the accuracy of the estimation.

9061-87a

Wireless sensing based bridge decentralized condition monitoring

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Decentralized monitoring is a recent research focus for the online condition assessment of large-span flexible bridge structures. This paper presents a decentralized condition monitoring method for beam-like truss structures with a lab verification test study. According to structural geometrical layout, the structure is divided into multiple local subgroups firstly. Based on vibration test within each subgroup, structural dynamic flexibility matrix of each measured subgroup is estimated and structural damage locating vector can be computed. The vector is taken as an input force vector imported into structural baseline FEM model to calculate the normalized cumulative stress of all components of the tested subgroup. Structural damage can then be detected and located by checking whether the obtained normalized cumulative stresses for the components in this subgroup are below a preset threshold value. The final decisions on structure damage occurrence and location are made by comparing the results obtained from different subgroups. Since the algorithm rely on an accurate baseline model during the local computing, parametrical and physical modeling error will induce some unpredictable effect on damage diagnosis and is carefully checked in this study. A numerical study on a planar cantilever beam-like truss is conducted to demo the procedure and inspire the discussion. The results tell that both the distribution and the level of the parametrical modeling error will have some influence on damage diagnosis conclusions. The physical modeling of the baseline structure as a frame model with rigid connection will not affect the result of damage diagnosis if the damage level is set to be 20%.

9061-88a

Global assessment of a cable-stayed bridge model using SNLSE approach

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Global assessment of structural conditions is important for structural health monitoring system. In particular, online or almost online structural parametric identification, based on vibration data measured from sensors, has received considerable attention recently. However, the problem becomes more challenging when the structure is complex and the number of degree-of-freedom (DOF) is large. A newly proposed time domain analysis methodology, referred to as the sequential nonlinear LSE (SNLSE) approach, has been studied and shown to be useful for the online tracking of parameters for structures with small DOFs. In this paper, the SNLSE approach will be applied for global assessment of an experimental cable-stay bridge model with large DOFs. A dynamic equivalent model of the bridge will be established and finite element analysis will be carried out to formulate the equation of motion. Numerical analysis will be conducted with different simulated damage scenarios and limited number of response data is considered. The capability of the proposed SNLSE approach in identifying the structural parameters and assessing the structural conditions will be verified.

9061-89a

Cyber-physical system for building structures using a flexibility-based damage detection method

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The detection and localization of damage in a timely manner is critical in order to avoid the failure of structures. When a structure is subjected to an unscheduled impulsive force, the resulting damage can lead to failure in a very short period of time. As such, a monitoring strategy that can adapt to variability in the environment and that anticipates changes in physical processes has the potential of detecting, locating and mitigating damage. These requirements can be met by a cyber-physical system equipped with Wireless Smart Sensor Network (WSSN) systems that is capable of measuring and analyzing dynamic responses in real time using on-board in network processing. The decentralized cyber-physical system uses the Angles-Between-String-and-Horizon (ASH) flexibility-based method to determine damage existence and location across the structure. The rapid condition screening is implemented on a potentially damaged structure and compared to an original baseline calculation, hence providing a supervised learning environment. An experimental laboratory study on a 5-story shear building with a damaged column subjected to an impulsive force has been chosen to validate the effectiveness and timeliness of the developed system proposed to detect, locate and mitigate damage.

9061-90a

Substructure parameter estimation for shear structures with limited measurements and unknown structural mass

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In this paper, a substructure identification method is proposed to estimate the parameters of any story in a shear structure with only limited floor accelerations and unknown structural mass. A shear structure is divided into substructures consisting of a series of a two-story standard substructure; two identification problems are formulated for the standard substructure using the cross power spectral densities (CPSD) of structural responses, each of which identifies the parameters of one story given that the parameters of the other are known. A loop identification scheme is proposed by connecting the two identification problems in a loop manner, forming a sequence of estimation problems to directly identify both story parameters of the standard substructure. If the structural masses are unknown, this loop identification method can still be applied to estimate mass normalized structural parameters as well as the relative mass distribution of the structure. The convergence condition is derived for the loop substructure identification, showing that the loop identification sequence is conditionally converged and some structural responses play a crucial role in determining the convergence. To ensure the convergence, a reference selection method is proposed, which uses a synthesized response, formed by a linear combination of the measured responses, as the reference response to calculate the CPSD of structural responses and to perform the loop substructure identification. A 10-story shear building is used to verify the convergence condition and to demonstrate that the proposed reference selection method does provide the converged and accurate estimation results.

9061-91b

Numerical and experimental characterizations of piezoresistive MEMS strain sensors

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In this paper, new MEMS strain sensors are introduced. The transduction principle of the sensors is the resistance change due to piezoresistive property of polysilicon. Five different sensors are designed on the same device and tuned to resistance values of 350 ? and 120 ?. The sensors are aligned in horizontal, vertical and 45° directions in order to extract the principle strains. The geometry of the sensing element is a rectangular bar anchored at two ends and suspended above silicon substrate. The sensors are numerically modeled using COMSOL Multiphysics software.

The model consists of all the micromachining layers, including silicon substrate, 0.7 ?m thick polysilicon layer (sensing element) sandwiched between two layers of 0.35 ?m thick silicon nitride layers and trenching under polysilicon layer, in order to estimate the strain that piezoresistive element is exposed to. The MEMS strain sensors are manufactured using MetalMUMPs process. The sensors are attached to aluminum and steel plates, and their gauge factors are compared with conventional foil gauges under uniaxial and biaxial loading. It is demonstrated that the MEMS strain sensors can detect both static and dynamic strains with the gauge factor reaching significantly high values. High gauge factor occurs because of unique geometry design and trenching, which amplify the strain that the polysilicon layer senses. The MEMS strain sensor can be fused with other sensing elements on the same device such as accelerometer, acoustic emission in order to have redundant measurement from a single point.

9061-92b

Very low frequency/high sensitivity triaxial monolithic inertial sensor

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This paper describes a new mechanical implementation of a triaxial inertial sensor [1] [2], configurable as seismometer, velocimeter and/or as accelerometer, consisting of three one-dimensional monolithic FP sensors, suitably geometrically positioned, small (<10 cm) and very light (<200 g). The triaxial sensor is, therefore, compact, light, scalable, tunable instrument (frequency < 100 mHz), with large band (10^-7 Hz - 100 Hz), high quality factor (Q > 2000 in air) with good immunity to environmental noises, guaranteed by integrated laser optical and/or electromagnetic modular readouts. The measured sensitivity curve is in very good agreement with the theoretical ones (<10^-14 m/sqrt(Hz) in the band (0.1 - 10 Hz). Typical applications are in the field of earthquake engineering, geophysics, civil engineering and in all applications requiring large band-low frequency performances coupled with high sensitivities, but also in ultra high vacuum and/or cryogenic applications.

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9061-93b

The model and scale factor of a MEMS vibratory rotation rate sensor

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Vibratory MEMS gyroscopes are used to measure rotation rate and have applications in consumer electronics, vehicle safety systems, and aerospace industry. The model of a new vibratory MEMS gyroscope is derived. The sensor is made of a cantilever microbeam with an attached end-rigid body. It is shown that introducing the rigid body formulation of the end-mass modifies the static and dynamic of the sensor. The sensor includes drive and sense electrodes. Conventionally, the gyroscopes are operated in the amplitude-modulation mode. Recently, the frequency-modulated mode has been introduced which provides an unrestricted bandwidth. It is shown that the sensor can operate in the amplitude-based mode and the frequency-based mode. The mechanical scale factor is an important parameter in characterizing the performance of microgyroscopes. The method of computing the mechanical scale factor for the proposed microsensor is formulated in this work.

9061-94b

Compressive Piezo-floating-gate sensors for self-powered sensing of wide-dynamic-range mechanical events

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One of the challenges in designing self-powered sensors or sensors that scavenge energy directly from the signal being sensed is the threshold effect. The sensor electronics typically requires minimum energy threshold energy for start-up or to be operational where as the maximum operational energy for the sensor is determined by the breakdown or heat dissipation characteristics of the electronic components. The minimum and maximum energy thresholds limit the overall operating and sensing range for the self-powered sensor and pose a significant problem for applications such as monitoring the health of armors due to ballistic impacts. For example, the velocity of a bullet impinging the armor could be as high as 800m/s with impact energy exceeding 100J, and depending on the placement of the sensor and the point of impact, the mechanical strain could vary over several orders of magnitude. In this paper we describe a novel compressive self-powering approach that significantly extends the sensing range of our previously reported self-powered piezo-floating-gate (PFG) sensors. At the core of the proposed technique is a non-linear impedance circuit that dynamically loads the output of a piezoelectric transducer in a manner such that the sensor can be self-powered at low-levels of mechanical strain and yet is able to sense and detect large variations in strain-levels. Measured results obtained from fabricated prototypes and chipsets are presented and validate the proposed compressive self-powering approach.

9061-95b

Development of metamaterial based low cost passive wireless temperature sensor

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Wireless passive temperature sensors are gaining increasing attention due to the ever-growing need of precise monitoring of temperature in high temperature energy conversion systems such as gas turbines and coal-based power plants. Unfortunately, the harsh environment such as high temperature and corrosive atmosphere present in these systems limits current solutions. In order to alleviate these issues, this paper presents the design, simulation, and manufacturing process of a low cost, passive, and wireless temperature sensor that can withstand high temperature and harsh environment. The temperature sensor was designed following the principle of metamaterials by utilizing Split Ring Resonators (SRR) embedded in a dielectric matrix. The proposed wireless, passive temperature sensor behaves like an LC circuit that has a resonance frequency that depends on temperature. A full wave electromagnetic solver Ansys Ansoft HFSS was used to perform simulations to determine the optimum dimensions and geometry of the sensor unit. The sensor unit was prepared both by 3D-printing and powder-binder compression. After obtaining the unit it was sintered to achieve full density and better hardness. Wireless temperature sensing capability will be demonstrated using microwave generated by a network analyzer. The testing results will be compared with simulation and provide guidelines toward the development of low cost harsh environment wireless temperature sensors.

9061-96b

Investigation of a novel two dimensional photonic crystal sensor using microcantilever embedded with nano-ring resonators

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Microcantilever sensors have been known as a fundamental design in force sensors, strain sensors and biochemical sensors. The fast-growing applications in nanoelectromechanical systems (NEMS) lead to strong demands in new sensing mechanism in order to downsize the sensing elements to nanometer scale. With advantages of ultracompact size, high resolution, and easy integration, photonic crystal (PC) based resonator have been investigated as promising solution. The performances of these sensors are mainly determined by microcantilever and nano-ring respnators. The output wavelength of these sensors using photonic crystal varies as a function of force and strain.

In this study, a novel two dimensional photonic crystal sensor, in which nano-ring resonators are embedded in an L-shaped elastic body, is developed and studied numerically. The relationship between the force or strain and the output wavelength is obtained using finite element method and finite difference time-domain method, respectively. The effect of the nano-ring resonator geometry, length of the microcantilever, materials of photonic crystal and application environment are investigated. In addition, a comparison between the numerical and theoretical results is provided.

9061-97b

Capacitance-based damage detection sensing for aerospace structural composites

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Damage detection technology needs more improvement for aerospace engineering application because detection within complex composite structures is difficult yet critical to avoid catastrophic failure. Damage detection is difficult in aerospace structures as no single damage detection technology can cover the various defect types (delamination, fiber fracture, matrix crack etc.), or conditions (visibility, crack length size, etc.). These defect states are expected to become even more complex with future introduction of novel composites including nano-/micro-particle reinforcement. Currently, non-destructive evaluation (NDE) methods with X-ray, ultrasound, or eddy current have good resolutions (< 0.1 mm), but their detection capabilities is limited by defect locations and orientations and require massive inspection devices. System health monitoring (SHM) methods are often paired with NDE technologies to signal out sensed damage, but their data collection and analysis currently requires excessive wiring and complex signal analysis. Here, we present a capacitance sensor-based, structural defect detection technology with improved sensing capability. Thin dielectric polymer layers are integrated as the part of the structure; the defect in the structure directly alters the sensing layer's capacitance, allowing full-coverage sensing capability independent of defect size, orientation or location.

In this work, we demonstrated this capacitance-based detection by applying the sensing layers on the surfaces of two substrates: carbon-fiber reinforced plastic (CFRP) as a common aerospace structural material, and carbon nanotube (CNT) prepreg as a novel nano-engineered material. Parylene C, a poly(p-xylylene) polymer, was selected as the dielectric layer because the polymer can be conformally coated and has a relatively high melting temperature (~290 oC). The substrate samples were deposited with bottom gold (~0.2 um) electrodes by e-beam evaporation, with Parylene C (~1 um) by chemical vapor deposition, and with top patterned square Au electrodes (~0.2 um, 1mm ? 1mm). The method of structural damage detection then simply involved recording the change in capacitance introduced by the damage. A topological map of capacitance change is created to pinpoint the damage location(s).

In our tests, a damage of ~1 mm diameter was introduced on the surface by indentation. When compared before and after damage introduction, the capacitances between the top and bottom electrodes decreased by ~1% regardless of the substrates: 0.3pF change for CFRP (~30pF capacitance as deposited), and 0.9 pF change for CNT prepreg (~100pF capacitance as deposited). These capacitance changes can be attributed to decreased electrode pad sizes and/or decreased effective dielectric constant by crack introduction. The defect location was successfully mapped by capacitances measured on multiple electrode pad locations, proving the capability of 2D pin-point defect detection.

The capacitance-based structural damage detection is with structural integrity and light-weight, and thus suitable for aero/astro structures such as cryogenic tanks and rocket fairings. In addition, the technology is expected to have room for tailoring to accommodate new structures, materials, and corresponding requirements. For example, the thin dielectric sensing layers can be smoothly integrated between CFRP prepreg layers for 3D pin-point sensing capability. Electrode patterns or sensing layer thickness can be tailored for a wide range of detectable crack length (down to ~10nm) to be suitable for novel nano-/micro-engineered materials. Dielectric layers can be substituted for piezoelectric layers for passive sensing capability. Our next steps include 3D sensing layer design and its experimental evaluation, and mechanical characterization for structural integrity.

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9061-98b

Optimal design of a mechanically decoupled six-axis force/torque sensor based on the principal cross coupling minimization

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Six-axis force/torque(F/T) sensor which measures three force component (Fx, Fy, Fz) and three torque component (Mx, My, Mz) has been widely used in robotics applications. Recent demands of F/T sensor on automation and Human-Robot Interaction (HRI) technology have been growing in various industries and engineering researches such as humanoid robot, medical robot and civil engineering as well.

In developing mechanically decoupled six-axis F/T sensor, reducing cross coupling error is most important design consideration. Ad hoc selection and modification of design variables would not guarantee the sensor design with global minimal error and is not time efficient. Therefore, we proposed design optimization of a mechanically decoupled six-axis F/T sensor by minimizing principal coupling which is the biggest cross coupling.

For optimal design of the F/T sensor, the locations of twenty four strain gages are firstly determined using FEM and structural design variables are selected. Then the optimization is conducted minimizing principal coupling with several constrains on isotropy of output strains and safety of the structure. For effective optimization, FEM software and MATLAB are utilized interactively. As a result, principal coupling was reduced from 35% to 2.5% in finite element analysis which is hard to be obtained in mechanically decoupled six-axis F/T sensors. In experimental verification, there was 0.7% difference in principal coupling and 5.1 % difference in overall between numerical and experimental results. The design formulation and framework for optimization proposed in this study are expected to promote researches on multi-axis F/T sensors and their commercialization in various fields.

9061-100a

Predicting full-field dynamic strain on a three-bladed wind turbine using three-dimensional point tracking and expansion techniques

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Health monitoring of wind turbines is usually performed by collecting real-time operating data on a handful of points using traditional sensors such as accelerometers or strain-gages located on the nacelle. Although many wind turbine stop to operate because of damage in their blades, there are few to no sensors mounted to the turbine blades. Placing sensors on the rotating part of the structure is a challenge due to data transmission problems and mass-loading effects. Therefore, a current area of interest to the wind industry is how to monitor the condition of rotating blades using new sensing approaches that have non-contacting and distributed sensing capability over a large area while not adding significant cost or affecting the performance of the structure. Stereophotogrammetry and three-dimensional point tracking (3DPT) have allowed for new opportunities for blade inspection and structural health monitoring in wind turbines.

As part of a project to predict dynamic strain in rotating structures (e.g. wind turbines and helicopter blades), an experimental measurement was performed on a wind turbine attached to a 500-lb steel block and excited with a shaker. A wind turbine consisted of three 2.3-meter blades and a hub was placed on a semi-built-in condition using a shaft, a machining chuck, and a steel block. Several optical targets were distributed along the blades and the fixture. The turbine was excited at its resonant frequencies using a shaker and the dynamic displacements of the optical targets during the excitation were measured with a pair of high-speed cameras. Furthermore, a finite element (FE) model of the blades was also developed using three-dimensional solid elements. The FE mode shapes of the single blade in a cantilevered configuration were extracted by performing an eigensolution on the FE model. Using the FE mode shapes of the blades in conjunction with an expansion technique, the limited set of measured data was augmented to extract displacements at all the nodes of the finite element model. The expanded displacements were applied to the finite element model to predict the full-field dynamic strain in the blades. To validate the technique for dynamic strain prediction, the dynamic strain at eight locations of the blades was measured during excitation by using strain-gages. The strain predicted by using the stereophotogrammetric measurement and expansion algorithm compares well with the strain-gage results. The results of the paper also show that for a turbine located in the semi-built-in configuration and excited at resonant frequencies of the turbine, the expansion algorithm can be performed using the modes of the single blades in a cantilevered configuration.

9061-160a

Monitoring of wind pressure distribution at a supertall structure above maximum gradient wind level

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While the field measurement of wind speed at buildings and towers has been made by numerous investigators, the direct measurement of wind pressure at high-rise structures was seldom reported. Up to now, the information regarding wind pressure distribution above the maximum gradient wind level (it is 450 m stipulated in the Chinese code) has never been experimentally obtained. This paper presents a field monitoring investigation on the measurement of wind pressure and its distribution at the Canton Tower of 600 m high above the maximum gradient wind level during the typhoon Kaitak. The main purpose of this monitoring program is to identify the type of probability distribution, dependence of coherence upon distance, and coherence decay factor of the wind pressure around the maximum gradient wind level, and to provide field monitoring data for modeling the wind pressure time-histories by the proper orthogonal decomposition (POD) technique and verifying the reconstruction and prediction capabilities of the formulated model. For this purpose, a total of 24 wind pressure sensors have been deployed on the antenna mast of the Canton Tower at three levels of 495 m, 502 m, and 510 m, with eight being positioned at the eight sides of the octagonal section for each level. In addition, a propeller-type anemometer has been installed on the top of the main tower (461 m high) for wind speed and direction measurement. The sampling rate for both the pressure sensors and anemometer is set as 50 Hz. With the monitoring data, the probability distribution of the wind pressures, the vertical decay factor under different distances and the vertical coherence function have been obtained. Making use of the POD technique and the monitoring data from nine selected measurement points, a mathematical model is formulated to reconstruct and predict the time-histories of wind pressure distribution.

9061-101b

Implementation of a piezoelectric energy harvester in railway health monitoring

Jingcheng Li, Shinae Jang, Jiong Tang, Univ. of Connecticut (United States)

With development of wireless sensor technology, wireless sensor network has shown a great potential for railway health monitoring. However, how to supply continuous power to the wireless sensor nodes is one of the critical issues in long-term full-scale deployment of the wireless smart sensors. Some energy harvesting methodologies have been available including solar, vibration, wind, etc; among them, vibration-based energy harvester using piezoelectric material showed the potential for converting ambient vibration energy to electric energy in railway health monitoring even for underground subway systems. However, the piezoelectric energy harvester has two major problems including that it could only generate small amount of energy, and that it should match the exact narrow band natural frequency with the excitation frequency. To overcome these problems, a wide band piezoelectric energy harvester which could generate more power on various frequencies regions has been designed and will be implemented in full-scale field tests using actual railway train. Before designing the piezoelectric energy harvester, the vibration characteristics of the railway track has been determined by system identification of field acceleration data. Based on the excitation frequency band width and the amplitude, the wide band piezoelectric energy harvester has been designed and optimized to increase power generation. The power generation will be compared to a narrow-band, resonant-based, piezoelectric energy harvester. Field test results showed that the power generation from the wide band piezoelectric energy harvester has been much higher than the resonant harvester at the same vibration condition when a train passed by.

9061-102b

Fault detection in railway track using piezoelectric transducer

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Because of their two-way electro-mechanical coupling characteristics, piezoelectric transducers are used as actuators and sensors in a wide variety of applications. The advantages of such transducers include high bandwidth and easy integration, which make them appealing for the real-time, online monitoring of the health condition of railway tracks. In this research, we develop feasibility study of using piezoelectric transducers to detect the occurrence of structural damage and foreign object in actual railway track. Specifically, we investigate railway track damage detection using impedance approach and wave propagation approach, and establish damage metrics for the respective approaches and compare the performance. We further explore the sensing enhancement by integrating resonant circuit to the transducers to amplify the response anomaly. Comprehensive analytical and experimental studies are carried out for demonstration and illustration.

9061-103a

Affordable and personalized lighting using inverse modeling and virtual sensors

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Wireless sensor networks (WSN) can enable personalized intelligent lighting systems while reducing building energy use by 50-70%. As a result WSN systems are being increasingly integrated in state-of-art intelligent lighting systems. In future these systems will enable participation of lighting loads as ancillary services. However, such systems can be expensive to implement and lack true plug-and-play quality for user-friendly commissioning. In this paper we present a combination of WSN and modeling software, that holds the potential of improving affordability and user-friendliness of WSN enabled intelligent lighting system. The system requires ~60% fewer sensor deployments compared to state-of-art systems. Reduction in sensor deployments was achieved by replacing the actual photo-sensors with real-time inverse predictive models of discrete indoor light distribution. The predictive models use Piece-wise linear regression on spatially sparse and clustered sub-hourly photo-sensor data. Clustering by 30 minutes mean and standard deviation of outdoor light is used as a proxy for sky conditions. The sub-hourly division of the data accounts for daily course of solar azimuth and altitude. This algorithm also determines the optimal photo-sensor placement for the best predictability of the light field. Using 2 weeks of daylight and artificial light training data acquired at Sustainability Base at NASA Ames, this model was able to predict the light level at seven monitored workstations at ~5-15% accuracy. We estimated that 10% adoption of this intelligent wireless sensor system in commercial buildings can save 0.2-0.25 quads BTU energy nationwide. Future work will include testing the spatio-temporal scalability of the inverse model framework.

9061-104a

Lighting control system reflecting both human movement and feelings using voice

Yoko Yamagishi, Akira Mita, Keio Univ. (Japan)

Recently, intelligent spaces which robotize the spaces by embedding sensors or technologies are studied to provide new services and meet various demands. However, since it is designed based on scenarios, it is difficult to manage unexpected circumstances and change flexibly to fill demands which vary depending on aging and emotions day by day. Therefore, we suggest “Biofied Buildings” in which building sensor, analyze, study and act by itself based on human’s movement and emotion to create safety, comfortable and eco-friendly space.

In this paper, we would like to propose a lighting control system which takes into account not only human’s movement or scenes but also human’s feelings. We believe this system is essential because there is lighting system which change illuminance and color temperature based on only scene or movement, for instance when residents are watching a movie, the light will be turned into low illuminance and low color temperature, but appropriate lighting is varied depending on emotion as well. Therefore proposed system would take into account feelings which are detected by voice and they play the role of a control signal. Especially we would like to consider the system which relieves negative feelings such as anger or sadness by controlling illuminance and color temperature since it is known that colors have certain effect on human’s mind. The proposed system enables to reduce negative feelings and have possibility to be applied for medical service such as depressive psychosis.

9061-105a

Smart lighting control system using sensor agent robots based on Homeostasis and nervous system

Momoko Tokiwa, Akira Mita, Keio Univ. (Japan)

In our laboratory, for responding flexibly to unexpected events and needs that are caused by aging and complicated emotional shift, we suggested “Biofied Building”. In Biofied Building, we propose that residents have sensor agent robots, and it is the remarkable point that the robots detect resident’s emotion by their sign and motion and control devices in the space. The goal of Biofied Building is that the spaces satisfy the demand of comfort, energy efficiency and safety by embedding adaptive functions learnt from life into buildings. Among others, we focus on Homeostasis mechanism that keep of the human internal environment constant. We can maintain the space in comfortable condition by imitating this mechanism. Until now, we have focused on lighting environment and studied the lighting control system imitating the endocrine system and the immune system. However, we can’t satisfy the demand of the residents who want to turn up or down the light immediately. Thus to overcome this drawback we propose a new system which works by combining the endocrine system, the immune system and the nerve system. As the nerve system can deliver the signals immediately, the control system should work promptly. By applying Sensor Agent Robots and the LED system using Wi-Fi and the cloud, I verified the real-time practical effectiveness of the system. The robots follow the human and estimate the internal state by their motion and sign, the devices works to satisfy their needs. I state that the system can control the illuminance under different conditions.

9061-106a

A model for earthquake acceleration monitoring with wireless sensor networks in a structure

Takahiro Fujiwara, Yugo Nakamura, Hakodate National College of Technology (Japan); Kousei Jinno, Hideyuki Uehara, Toyohashi Univ. of Technology (Japan)

Wireless sensor networks (WSNs), which autonomously construct a wireless network and collect data speedily, have attracted much attention to a technology for realizing ubiquitous society. WSNs, therefore, have been studied mainly to collect environmental data so far, such as temperature, humidity, acceleration, light intensity, acceptable to gather data in a long interval. Structural health monitoring (SHM), meanwhile, requires a high-speed operation to detect quick variance of phenomena, such as vibration or impact. To detect damage in case of earthquake, SHM collects seismic acceleration in the ground or on structures using high sensitive accelerometers, which are connected to a recorder by cables. Such a monitoring system needs a lot of budget and less flexibility to install sensors. WSN, on the other hand, is capable of connecting nodes by wireless networking technologies, and building a network autonomously. One issue to introduce WSN in SHM is to detect phenomena at a high sapling rate under energy-aware conditions. In this paper, we propose a model of seismic acceleration monitoring with WSN, and indicate fundamental examination results using a test bed of the monitoring system. The experimental system showed it is capable of collecting acceleration at a rate of 100 sampling per second (sps) by multi-hopping, and gathering data in a database through WSN and a

wireless distribution system (WDS) in a real time operation. We also show usefulness of intermittent operation of WSN in acceleration monitoring, by selecting appropriate sampling rates, based on the analysis of seismic acceleration measured in a structure.

9061-107b

Compressed Sensing techniques for arbitrary frequency-sparse signals in structural health monitoring

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Structural health monitoring faces a fact that requires collection of large number sample data and sometimes high frequent vibration data for detecting the damage of structures. The expensive cost for collecting the data is a big challenge for structural health monitoring. The recent proposed Compressive Sensing method enables a potentially large reduction in the sampling, which is a new way to counter the challenge. The Compressed Sensing theory requires sparse signal, meaning that the signals can be well-approximated as a linear combination of just a few elements from a known discrete basis or dictionary. The signal of structure vibration can be decomposed into a few sinusoid linear combination in the DFT domain. Unfortunately, in most cases, the frequencies of decomposed sinusoid are arbitrary in that domain, which may not lie precisely on the discrete DFT basis or dictionary. In this case, the signal will lost its sparsity, which makes Compressive Sensing recovery performance degrades significantly. One way to improve the sparsity of the signal is to increase the size of the dictionary, but there exists a tradeoff: the closely-spaced DFT dictionary will increase the coherence between the elements in the dictionary, which in turn decreases recovery performance.

In this work we introduce three approaches for arbitrary frequency signals recovery. The first approach is the spectral compressive sensing, which is based on redundant DFT dictionary and a restricted union-of-subspaces signal model that inhibits closely spaced sinusoids. The second approach is the continuous basis pursuit that establishes continuous basis by introducing interpolation steps, and the continuous basis break the discretization barrier observed implicitly in Compressive Sensing. The third approach is an atomic norm minimization approach, which is also base on continuous basis, but there is no need to establish continuous basis, and the atomic norm will be reformulated as an exact semidefinite programing. The three approaches are studied by numerical simulation. Structure vibration signal is simulated by a finite element model, and compressed measurements of the signal are taken to perform signal recovery. Comparison of the performance of the three approaches is made, and future work on design of compressive sampling testing system for vibrational signal is proposed.

9061-108b

A novel unknown feature searching algorithm at pre-processing of data analysis

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It is well known that Machine Learning (ML) techniques are suitable data driven analysis with their classification and regression abilities. However often in practical applications of ML, out-of-box features are not considered as a part of analysis because these algorithms and tools only operate with given or known features. We propose a new algorithm that searches for unknown features at pre-processing stage of data analysis and connects them to known characteristics with associated weights. The algorithm first separates the separable datasets using maximum-margin hyperspace, similar to ordinary Support Vector Machines (SVM) algorithm. Then it searches non-separable sets in same high dimensional space and finds additional features for which users can select the initial conditions. To form the additional unknown features that separate the non-separable sets, backpropagation algorithm using multi-objective optimization is used for maximum-margin of hyperplane. For this study multiple wave propagation experimental results are used in which the specimens are subjected to a variety of conditions such as under ambient noise and different temperatures. The actuators/sensors also vary in their sizes and input powers. The inputs for the algorithm contain all possible known features except controlled conditions/features. Comparisons between output of algorithm and controlled conditions/features are performed to validate the proposed algorithm.

9061-109b

A new extension of unscented Kalman filter for structural health assessment with unknown input

Abdullah Al-Hussein, Achintya Haldar, The Univ. of Arizona (United States)

A time-domain nonlinear system identification (SI)-based structural health assessment (SHA) procedure, using Unscented Kalman Filter (UKF), will be presented in this paper. The procedure specifically assesses structural health in the presence of highly nonlinear behavior. It is a two-stage procedure. It integrates an iterative least squares technique and the unscented Kalman filter. The authors believe that the integrated procedure significantly improves the basic unscented Kalman filter concept. The procedure can assess the health of a structure using only a limited number of noise-contaminated acceleration time-histories measured at a small part of a structure and does not need information on input excitation. The structures are represented by finite element models and the location and severity of defect(s) are assessed by tracking the changes in the stiffness properties of individual elements from their expected values. With the help of examples, it will be demonstrated that the method is capable of accurately identifying the state of structures. Defect-free and defective states will be considered. Small and relatively large defects will be introduced at different locations in the structure and the capability of the method will be checked if it can detect the health. It will be demonstrated that the accuracy of the method is much better than the other methods currently available even when input excitation information was used for identification purpose. It is also superior to the extended Kalman filter concept for nonlinear system identification. Considering the accuracy and robustness, the procedure can be used as a nondestructive structural health assessment procedure.

9061-110b

Online damage detection based on the combination of successive displacement curvature under the influence of environmental temperature

Yabin Liang, Dalian Univ. of Technology (China)

The static displacement curvature of a structure could be used for damage detection, however, it will also be influenced by varying environmental and operational conditions at the same time, and finally induces large disturbances into identification result. Based on the unique character of the combination of three successive displacement curvature of a beam, which could detect structure damage without the influence of varying environmental temperature, a new damage identification index, i.e., combination of successive displacement curvature, is proposed in this paper, and the validity and effectiveness of the proposed method is illustrated in the simulation of a simply supported steel beam. simulation result demonstrate the proposed method could eliminate the influence of changing environmental temperature without structural original data in healthy condition, and monitor, diagnose and even identify damage location online accurately.

9061-99a

Research on fatigue damage detection for wind turbine blade based on high-spatial-resolution DPP-BOTDA

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In this paper, a fatigue damage detection system used for wind turbine blade is successfully developed by using high-spatial-resolution differential pulse-width pair Brillouin optical time-domain analysis (DPP-BOTDA) sensing system. A piece of polarization-maintaining optical fiber is bonded on the blade surface to form the distributed sensing network. A DPP-BOTDA system, with a spatial resolution of 20cm and sampling interval of 1cm, is adopted to measuring distributed strain and detecting fatigue damage of wind turbine blade during fatigue test using the differential pulse pair of 39.5ns/41.5ns. Strain and the Brillouin gain spectra changes from undamaged state to fatigue failure are experimentally presented. The experimental results reveal that fatigue damage changes the strain distribution especially around the high strain area, and the width, amplitude and central frequency of the Brillouin gain spectra are sensitive to fatigue damage as the stiffness degradation and accumulated cracks change local strain gradient. As the damage becomes larger, the width of the Brillouin gain spectra becomes broader. Consequently, location and size of fatigue damage could be estimated. The developed system shows its potentiality for developing highly reliable wind turbine monitoring system as the effectiveness of damage detection and distributed sensing.

9061-112a

Distributed strain monitoring for bridges: temperature effects

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To better manage infrastructure assets as they reach the end of their service lives, quantitative data is required to better assess structural behavior and allow for more informed decision making. Distributed fiber optic strain sensors are one sensing technology that could provide comprehensive data for use in structural assessments as these systems potentially allow for strain to be measured with the same accuracy and gage lengths as conventional strain sensors. However, as with many sensor technologies, temperature can play an important role in terms of both the structure’s and sensor’s performance. To investigate this issue a fiber optic distributed strain sensor system was installed on a section of a two span reinforced concrete bridge on the TransCanada Highway. Strain data was acquired several times a day as well as over the course of several months to explore the effects of changing temperature on the data. The results show that the strain measurements are affected by temperature effects on both the fiber and on the bridge as a whole. The strain measurements due to temperature are compared to strain measurements that were taken during a load test on the bridge. The results show that even a small change in temperature can produce crack width and strain changes similar to those due to a fully loaded transport truck. Future directions for research in this area are outlined.

9061-113a

Optical fiber sensors with flexible encapsulation for pavement behavior monitoring

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Due to the increasing needs for robust highway pavement structural monitoring tools with high accuracy and functionality, this paper introduces some preliminary outcomes from our research on developing an optical fiber based pavement behavior monitoring sensing system. The major content of this paper discusses the sensing system design concept and a novel optical fiber flexible encapsulation technique. The proposed sensing system integrates Fiber Bragg grating (FBG) and Brillouin Optical Time Domain Analysis/Reflectometry (BOTDA/R) techniques to ensure the large coverage and local high accurate monitoring. A new encapsulation technique for optical fiber has been proposed to overcome the difficulties in withstanding the harsh working environment in pavement structures. Lab and field tests have also been carried out to study the effectiveness of the proposed flexible encapsulation method. The sensors with the flexible encapsulation show high “survival rate” (>75%) after installation in a mini test track. The field test data also proves the potential of using optical fiber based sensors for pavement structure shrinkage monitoring and life cycle performance monitoring in a wide range.

9061-114a

On the use of electrical and optical strain gauges paired to magnetostrictive patch actuators

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Giant Magnetostrictive Actuators (GMA) can be profitably used in application of vibration control on smart structures. In this field, the use of inertial actuators based on magnetostrictive materials has been consolidate. Such devices turn out to be very effective in applications of vibration control, since they can be easily paired with sensors able to ensure the feedback signal necessary to perform the control action.

Unlike most widespread applications, this paper studies the use of patch magnetostrictive actuators. They are made of a sheet of magnetostrictive material, rigidly constrained to the structure, and wrapped in a solenoid whose purpose is to change the intensity of the magnetic field within the material itself.

The challenge in the use of such devices resides in the impossibility of having co-located sensors. This limit may be exceeded by using strain gauge sensors to measure the deformation of the structure at the actuator. This work analyzes experimentally the opportunity of introducing, inside a composite material structure, both the conventional electric strain gauges and the less conventional optical sensors based on Bragg’s gratings.

The performance of both solutions are analyzed with particular reference to the signal to noise ratio, the resolution of the sensors, the sensitivity to variations of the electric and magnetic fields and the temperature change associated with the operation of the actuator.

9061-115a

Novel braided composites with integrated optical fibre sensors

Andrzej Czulak, Werner Hufenbach, Maik Gude, Technische Univ. Dresden (Germany)

Optical fibre sensors in the form of Bragg Fibre Gratings (FBGs) and Reyleigh Sensors were integrated in braided glass fibre preforms and consequently used for monitoring the whole manufacturing process as well as static pressure tests of the prepared high pressure vessels. A device for automated integration of optical fibre sensors was developed to upgrade the braiding wheel at „Institut für Leichtbau- und Kunststofftechnik“ (Institute of Lightweight Construction and Polymer Technologies) of TU Dresden.

The integration of optical fibre sensors in the braiding process allows online monitoring of every manufacturing step as well as structure health monitoring during product lifetime. While their automated integration in the braiding process shows a high potential for cost-effective application in industrial scale production.

9061-116b

Fourier-based design of acoustic strain rosettes

Massimo Ruzzene, Matteo Carrara, Georgia Institute of Technology (United States)

The paper reports on the design of surface acoustic wave strain sensing devices based on a Fourier approach. A patterned sensing surface acts as a narrow band filter for surface acoustic waves. The center frequencies vary as functions of the amount of strain present in the sensing area, and can be thus used to estimate the surface strain. The design of the sensing pattern in the Fourier space allows the selection of multiple sensing frequencies and for their shifting characteristics to be related to the three components of strain, i.e. two normal and one shear. The result is a surface acoustic wave strain gauge that acts as a strain rosette.

The design procedure formulates the problem in the wavenumber domain, whereby the radiation characteristics of the sensing surface in response to an incident broadband surface wave are selected to ensure sensitivity to all three strain components. The concept is first illustrated for a one-dimensional pattern, whose radiation characteristics are governed by a simple, scalar, grating equation. The design approach is then extended to a two-dimensional pattern to demonstrate the ability to simultaneously measure all three surface strain components. The rosette-like operation of the considered strain sensor is demonstrated through numerical simulations conducted on an elastic surface subjected to various strain states.

9061-117b

Miscellaneous Lamb wave phased array imaging with hybrid PZT-SLDV sensing

Zhenhua Tian, Lingyu Yu, Univ. of South Carolina (United States)

Lamb waves have proved useful for structural health monitoring (SHM) and nondestructive evaluation (NDE) due to their ability to propagate long distances with less energy loss and sensitivity to small defects in the structure. However, there remain many challenging tasks for the development of effective damage imaging technique for SHM due to the dispersive and multi-modal nature of Lamb waves. An additional challenge for practical Lamb wave application is the limited accessible area for damage inspection.

This paper presents a novel Lamb wave phased array imaging by using a hybrid PZT-scanning laser Doppler vibrometer (SLDV) system and miscellaneous modes. Phased arrays use sensors physically placed close to each other and receive waves from a specific direction such that allows for sensing of a large area from a single position. In our study, a hybrid array system is developed consisting of a surface mounted PZT to generate Lamb waves and a non-contact SLDV to acquire high spatial resolution time-space wavefield remotely. The time-space wavefield measurements contain multiple Lamb modes that propagate in different directions in the structure. Frequency-wavenumber decomposition is then applied to decompose the original wavefield into individual wave modes and waves propagating in different directions. With the decomposed components, frequency domain phased array beamforming with various Lamb wave modes is developed to detect the damage, providing miscellaneous information regard the damage. The beamforming in frequency domain shows that the Lamb wave dispersive effect can be mitigated.

9061-118b

Simulation of shear wave propagation induced by acoustic radiation force

Jae-Wook Jung, Jung-Wuk Hong, KAIST (Korea, Republic of)

Acoustic radiation force is a physical phenomenon caused by propagation of ultrasound in an attenuating medium. When ultrasound propagates in the medium, the momentum of propagating ultrasound is transferred to the medium due to absorption mechanism. As a result, acoustic radiation force is generated in the direction of waves. By focusing the ultrasound at a specific location for a certain period, we can exert the acoustic radiation force at the location and generate shear waves. Characteristics of the shear wave critically depend on the material properties. Therefore, the shear wave propagation in the medium containing an inclusion shows differences compared to the wave in the pure medium. In this paper, we simulate acoustic radiation force and shear wave by using the finite element method. The purpose of this study is to estimate the properties of the inclusion by analyzing the change of the shear wave in the almost incompressible material considering the existence of the inclusion.

9061-119b

Thermoacoustic effects on layered structures for the evaluation of structural parameters

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The temperature dependent material characteristics of a layered panel are experimentally measured on small composite samples using a Thermal Mechanical Analysis (TMA) configuration. The temperature dependent wave dispersion characteristics of the panel are subsequently computed using a Wave Finite Element Method (WFEM). The results are compared to Inhomogeneous Wave Correlation (IWC) measurements performed at different temperature and humidity levels. This phase aims at assessing the validity of the characteristics' extraction on samples for larger composite components' calculations and its sensitivity to environmental conditions.

The WFEM predictions are eventually used within a wave context SEA approach in order to calculate the temperature dependent Sound Transmission Loss (STL) of the layered panel. Results on the STL for temperatures varying between -100 oC to 160 oC are computed for a structure operating at sea level. The importance of the glass transition region on the panel's vibroacoustic response can hence be exhibited and discussed.

Furthermore, the thermal vibroacoustic effect on singularities signatures can be considered and evaluated in structural components. Thermal and humidity sensitivities of the results are also presented.

9061-120b

Recent trends in reinforcement corrosion assessment using Piezo sensors via electro mechanical impedance (EMI) technique

Visalakshi Talakokula, Indian Institute of Technology Delhi (India)

Corrosion of steel reinforcement in concrete is probably the most serious durability problem of reinforced concrete (RC) structures in modern times, which has been widely reported in the literature over the last three decades. Concrete ordinarily provides an almost ideal environment for protecting the embedded steel from corrosion due to the alkaline passive film surrounding the steel bar. However, the breakdown of this passive film, either due to chloride ions or due to carbonation, results in the corrosion of rebars. Reinforcement corrosion is one of the main causes of damage and premature failure of the RC structures worldwide, causing enormous costs for inspection, maintenance, restoration and replacement. Therefore, early detection of corrosion and timely remedial action on the affected portion can facilitate an optimum utilization of the structure, imparting longevity to it.

This paper presents a new corrosion assessment model based on the equivalent parameters extracted from the impedance spectrum of concrete-rebar system using the lead zirconium titanate commonly known as PZT sensors via electro mechanical impedance (EMI) technique. Although the EMI technique is well established for damage detection and quantification of civil, mechanical and aerospace structures, only limited studies have been reported for its application for rebar corrosion detection in RC structures. This paper presents the details of an accelerated corrosion study carried out on RC specimens covering both chlorination and carbonation induced corrosion using PZT sensors surface bonded on rebars as well as embedded inside the concrete. This is the first ever research reporting such an extensive studies on the application of the equivalent parameters for corrosion assessment of rebars in concrete.

9061-121a

FE model updating considering boundary conditions

Jong-Jae Lee, Sejong Univ. (Korea, Republic of)

Bridges are the natural assets to be properly managed for the safe operation and efficient maintenance. To make an accurate finite element (FE) mode for detailed investigations, it is required to correct initial FE model using measured responses. since boundary conditions may results in significant influences on the structural responses, it needs to construct FE model reflecting current boundary conditions. However, it is very difficult to measure rotational behaviours of boundaries, since the physical quantity is very small, e.g. rotational angle of the bridge supports. In this study, a novel sensing technique is proposed to measure the rotational angle of a support together with the displacement of the bridge deck under normal traffic loads. The boundary conditions are calibrated based on the measured data. Then, the FE model updating is carried out using ambient vibration data. The effectiveness of the proposed method was validated through field tests on a steel girder bridge in Korea.

9061-122a

Evaluating damage potential of cryogenic concrete using acoustic emission and LVDT sensors

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This study evaluates the damage potential of concrete of different mix designs subjected to cryogenic temperatures, using acoustic emission and linear variable differential transformer (LVDT) sensors. The aim is to investigate design methodologies that might be employed to produce concrete that resists damage when cooled to cryogenic temperatures. Such concrete would be suitable for primary containment of liquefied natural gas (LNG) and could replace currently used 9% Ni steel, thereby leading to huge cost savings. In the experiments described, cylindrical concrete samples, 75 mm diameter by 150 mm long, were cast using different mix designs. The mixes employed either river sand siliceous or manufactured limestone sand as fine aggregates. Moreover, limestone, sandstone, trap rock and light weight aggregate were individually used as coarse aggregates in the mixes. The concrete samples were then cooled from room temperature (20°C) to cryogenic temperature (-165°C) in a temperature chamber. LVDT and acoustic emission sensors were placed on the samples during the cooling process. The damage potential was evaluated in terms of the coefficient of thermal expansion (CTE) and the growth of damage as determined from acoustic emissions, as a function of temperature, cooling rate and concrete mixture design. Initial results demonstrate the effects of the difference in CTE between the mortar and aggregate and cooling rate on damage growth. The effect of air-entrainment on resistance of different concrete mixes to damage is shown. Work is in progress to fully understand thermal dilation and damage growth in concrete due to differential CTE of its components.

9061-123a

Design of strain sensors based on the resistivity percolation curves and piezoresistivity curves of conductive composites

Jinbao Jiang, Huigang Xiao, Hui Li, Harbin Institute of Technology (China)

This paper concentrates on conductive composites with conductive fillers and their use for strain sensing based on piezoresistivity. Percolation curves of resistivity were summarized and validated as the basic for the design of such conductive composites-made piezoresistivity-based strain sensors, with percolation zoon and percolation slope as the key. A detailed comparison between cement-based and resin-based conductive composites with fibrous and particulate fillers were made and discussed in this work for further understanding the design of such sensors based on percolation curves. Magnetic field was introduced as an extrinsic factor for the design of the percolation curves and further for the design of such sensors' piezoresistivity curves, which was proved to be quite an effective way. Concluded speaking, when making more full use of the designability of percolation curves, we can make better strain sensors used for structural health monitoring.

9061-124a

Structural condition assessment of reticulated shell structures and cable-net structures

Grace Yan, The Univ. of Texas at El Paso (United States)

Reticulated shell and cable-net structures are usually built for venues where hundreds of people assemble. Failure of this type of structure may endanger the safety of hundreds of people. Traditional vibration data-based approaches normally detect damage by investigating the change in modal parameters before and after damage. The modal parameters of this type of structure have two characteristics: 1) the natural frequencies of some modes are very close to each other, or even equal in an ideal situation, leading to the difficulty in modal identification; 2) the order of the mode may change due to the occurrence of damage, making the comparison of modal parameters of the same order before and after damage more difficult. Therefore, traditional approaches cannot deliver reliable damage detection results. In this study, a novel damage detection approach without using the baseline data will be proposed. First, an appropriate way to excite this type of structure will be proposed to facilitate the identification of modal parameters; second, a system identification approach that is suitable for close-frequency will be employed to identify modal parameters; finally, a damage indicator which reflects the change in axial strains of members will be proposed. This approach can directly localize damage to exact members. This approach does not require the baseline data. Numerical simulation and

experimental tests of two civil large-scale space structures, a reticulated shell and a cable-net structure, will be performed to validate the proposed approach.

9061-125a

Using multi-taper method to improve the accuracy of substructure identification for shear structures

Dongyu Zhang, Li Ni, Harbin Institute of Technology (China)

In the previous work by the authors, an inductive substructure identification method was proposed for a shear structure, which utilizes the Fourier transform of floor accelerations to formulate a series of inductive substructure identification problems, estimating the structural parameters from top to bottom iteratively. However, the simulation results shows that the proposed method can only obtain relatively accurate results when measurement noise is small. In order to improve the identification accuracy, an uncertainty analysis of the parameter identification errors is conducted for this method in this paper, revealing the important factors that influence the identification accuracy. Based on this result, a new substructure identification method is proposed herein, in which the cross power spectral densities of structural responses, computed via multi-taper method, are utilized to formulate the substructure identification problems. A similar uncertainty analysis of the identification errors is carried out for the new method, illustrating why the new method could significantly improve the identification accuracy. Finally, a numerical example of 8-story shear building structure is utilized to verify the effectiveness of the new multi-taper based substructure method in enhancing the identification accuracy.

9061-126a

Damage analysis tool package for steel and reinforced concrete buildings using acceleration data

Yu Suzuki, Akira Mita, Keio Univ. (Japan)

The Tohoku earthquake of magnitude 9.0 occurred on March 11, 2011 was the devastating event that resulted in collapse of many buildings and infra structures. The need for Structural Health Monitoring (SHM) was once again highlighted. The SHM system for building structures employs a variety of techniques including complicated system identification. Even though the system evolved significantly, there are only a few sets that are practically used. Two years ago, we created a tool package to verify the performance of seismic isolation buildings. Similar to this package, we decided to develop a tool package to evaluate the health status of steel and reinforced concrete buildings under large and small earthquakes. This package estimates the performance information such as natural frequencies, damping factors, story drift angles and the amount of absorbed energy et al. The package adopted the analysis methods such as the subspace method and ARX identification. In addition, combination of Random Decrement Technique with Wavelet analysis and a subspace method was employed for small input such as microtremors. The package is operated online and verified the effectiveness for real buildings of different structural types. The package showed promising feasibility for practical use.

9061-127a

Improvement of SA-based concrete crack monitoring with efficient data processing

Shuang Hou, Heying Zheng, Dalian Univ. of Technology (China)

In this study, smart aggregate (SA)-based crack monitoring method is proposed with a more efficient data processing. Though, the SA-based crack monitoring has been developed for a decade, most of the researchers uses the frequency sweep actuation for identifying the variation in frequency domain of the received signal, leading to a huge data processing time after event. To increase the data processing efficiency, this study attempts to use a single frequency actuation in a short time interval to substitute the frequency sweep and evaluates its effectiveness. Firstly, a concrete beams was designed with length of 2 m and a cross section of 0.12 m by 0.25 m. Four SAs are equally spaced in the beam with a distance of 0.6 m, with the first and the last SA 0.1 m apart from the two ends of the beam. The frequency sweep actuation was undertaken in the beginning to identify the frequency with the biggest amplitude in the received signal. Afterwards, an actuation with the identified frequency with only a few hundred cycles was applied and the received signals were compared in the process when the beam is subjected to a gradually deepening cut at a location between the actuating and receiving SAs. It is found from the results that single frequency actuation retained the same capacity in identifying the crack as the sweep frequency sweep actuation, while greatly reduced the computation demanding. Then monitoring method with the single frequency actuation was applied in the crack monitoring in the concrete column which was subjected to laterally cyclic loading that generates real crack in the column. The results also validated effectiveness of the single frequency actuation approach in identifying the cracks. Therefore it can be concluded that the proposed SA-based monitoring method is very efficient in data processing. This finding could lead to a continuously crack monitoring in an active manner in the future research.

9061-128b

Design and optimization of a morphing aileron control surface using FMC actuators

Edward B. Doepke, Michael K. Philen, Virginia Polytechnic Institute and State Univ. (United States)

Morphing aircraft have been a reappearing topic with a history as old as manned flight itself. Usually inspired by bird's ability to continually change the shape of their wings, many groups have focused on the use of smart materials for actuation in morphing concepts. This research will focus on the use of flexible matrix composite actuators (FMC) as a way to control the aileron of a commercial transport size aircraft. The FMC actuator is a high mechanical advantage system using stiff reinforcing fibers woven into a tube which can be pressurized to convert internal pressure to a mechanical force. Recently FMC actuators were used to in a full scale active spoiler model and tested under pseudo aerodynamic loading with promising results. Moving forward from this work a FMC aileron will be designed to achieve specifications similar to an existing commercial transport aircraft's aileron under full aerodynamic loads. The aileron will introduce several new design considerations including multiple actuation directions and actuation rates. This research will focus on taking the already proven designs for FMC based control surfaces and optimizing them for reduced system weight and reduced actuation power requirements. Current designs being considered use multiple materials ranging in Young's modulus from the kPa range for soft foams to GPa for metals and composites to achieve a structure that is sufficiently stiff to resist aerodynamic loading, yet soft enough to allow for efficient actuation. This wide material range combined with the inherent high strains in morphing designs and the complex load conditions from aerodynamics make designs difficult to analyze and optimize.

9061-129b

Health monitoring of fluid dampers for vibration control of structures: experimental investigation

Dimitrios Konstantinidis, McMaster Univ. (Canada); Nicos Makris, Univ. of Patras (Greece); James M. Kelly, Univ. of California, Berkeley (United States)

This paper presents results from a comprehensive experimental program on medium-size and large-size fluid dampers in an effort to extract their force output during cyclic loading by simply measuring the strain on the damper housing and the end-spacer of the damper. The paper shows that the experimental data obtained with commercially available strain gauges yield a force output of the damper that is in good agreement with the readings from the load cell. This comparison is achieved via the use of a position and velocity transducer, which combines good accuracy together with robust performance in a marine environment. The paper then examines the performance of a portable data acquisition system that can be used to collect and transmit data from a damper installed on a bridge. The data show that the proposed arrangement is promising for monitoring in situ the force output of fl uid dampers and detecting possible loss of their energy dissipation capability.

9061-130b

Miniature cryogenic valves for a Titan Lake sampling system

Stewart Sherrit, Wayne F. Zimmerman, Jet Propulsion Lab. (United States); Nobuyuki Takano, California State Polytechnic Univ., Pomona (United States); Louisa Avellar, Univ. of California, Berkeley (United States)

The Cassini mission has revealed Titan to be one of the most Earthlike worlds in the Solar System complete with many of the same surface features including lakes, river channels, basins, and dunes. But unlike Earth, the materials and fluids on Titan are composed of cryogenic organic compounds with lakes of liquid methane and ethane. One of the potential mission concepts to explore Titan is to land a floating Lander on one of the Titan Lakes and determine the local lake chemistry. In order to accomplish this within the expected mass volume and power budgets there is a need to pursue the development for a low power lightweight cryogenic valves which can be used along with vacuum lines to sample lake liquid and to distribute to various instruments aboard the Lander. To meet this need we have initiated the development of low power cryogenic valves and actuators based on a single crystal piezoelectric flextensional stacks produced by TRS ceramics Inc. Since the origin of such high electromechanical properties of Relaxor-PT single crystals is due to the polarization rotation effect, (i.e., intrinsic contributions), the strain per volt decrease at cryogenic temperatures is much lower than in standard Lead Zirconate Titanate (PZT) ceramics. This makes them promising candidates for cryogenic actuators with regards to the stroke for a given voltage. This paper will present our Titan Lake Sampling and Sample Handling system design and the development of small cryogenic piezoelectric valves developed to meet the system specifications.

9061-131b

Actively controlled ultrasonic squeeze film bearings: lateral movement and stability

Sebastian Mojrzisch, Leibniz Univ. Hannover (Germany)

In this paper the influence of lateral movement on ultrasonic squeeze film levitation bearings is presented. In non-contact bearing applications the use of ultrasonic levitation bearings is convenient, due to the not needed pressured air supply. However, these applications are generally high speed slider bearings with high lateral movement speeds. Therefore, the limits of ultrasonic levitation bearings are investigated by employing the Reynolds equation. Besides this, the effects of vibration on the stability of the bearing are considered.

9061-132b

Shape memory alloy (SMA)-based launch lock

Mircea Badescu, Yoseph Bar-Cohen, Xiaoqi Bao, Jet Propulsion Lab. (United States)

Most NASA missions require the use of a launch lock for securing moving components during the launch or securing the payload before release. A launch lock is usually used to prevent unwanted motion and secure the controlled components. The current launch locks are based on pyrotechnic, electro mechanically or NiTi driven pin pullers and they are mostly one time use mechanisms that are usually bulky and involve a relatively high mass. Generally, the use of piezoelectric actuation provides high precession nanometer accuracy but it relies on friction to generate displacement. During launch, the generated vibrations can release the normal force between the actuator components allowing shaft's free motion which could result in damage to the actuated structures or instruments. This problem is common to other linear actuators that consist of a ball screw mechanism. The authors are exploring the development of a novel launch lock mechanism that is activated by a shape memory alloy (SMA) material ring, a rigid element and an SMA ring holding flexure. The analytical model and the test results will be described and discussed in this paper.

9061-133b

Experimental evaluation of a neural-oscillator-driven active mass damper system

Daisuke Iba, Junichi Hongu, Kyoto Institute of Technology (Japan)

This paper denotes experimental evaluation results of a neural-oscillator-driven active mass damper system. One of the evaluation results is synchronization property of the embedded neural oscillator which has acceleration input from structures. The output of structures with sinusoidal input is measured by an accelerometer, and the obtained output is given to the oscillator as input. Then the relationship evaluation between the input and output of the oscillator is investigated. In addition, vibration control algorithm for determination of moving direction and distance of an auxiliary mass of the active mass damper is also experimentally evaluated. By comparison of the original limit-cycle and output of the oscillator with external input, the target position of the mass is derived, and according to the sign of the oscillator's output, the moving direction and timing are determined. The validation is carried out by experiment.

9061-134b

Finite element analysis of seal mechanism using SMA for Mars sample return

Xiaoqi Bao, Paulo J. Younse, Jet Propulsion Lab. (United States)

Returning Martian samples to Earth for extensive analysis is in great interest of planetary science community. Current Mars sample return architecture would require leaving the acquired samples on Mars for several of years before being retrieved by subsequent mission. Each sample would be sealed securely to keep its integrity. A reliable seal technique that does not affect the integrity of the samples and uses simple low-mass tool is required. The shape memory alloy (SMA) seal technique is a promising candidate. The performances of several primary designs of SMA seal for sample tubes were analyzed by finite element (FE) model. As the results of thermal heating characteristics had been reported in a previous presentation this paper will focus on the mechanical aspects including stress, strain and seal pressure induced by SMA actuation for various designs.

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9062-1

OTDR and OFDR for distributed multi-parameter sensing *(Invited Paper)*

Xiaoyi Bao, Univ. of Ottawa (Canada)

The drive for short spatial resolutions of millimeter scale distributed fiber sensors has pushed the interest in optical frequency domain reflectrometry (OFDR) systems. Because millimeters equivalent spatial resolution in optical time domain reflectrometry (OTDR) systems would require a data acquisition card with a bandwidth of 10 GHz and a sampling rate of tens of a few GSamples/s, such a digitizer or data acquisition card plus the pulse generator and detection system will make a distributed sensors very expensive. In the meantime the massive data points in OFDR have limited the sensing length of OFDR to less than 100m, if mm to cm spatial resolution remains. While OTDR sensors can reach over one hundred kilometer sensing length. The sensing parameters of temperature, strain, vibration and acoustic wave have been achieved with phase OTDR and OFDR system.

We demonstrate a high precision simultaneous temperature and strain measurement by polarization sensitive OFDR with temperature and strain accuracy of 0.8 deg and 7 micro-strains over a spatial resolution of 6.5 mm over 170-m fiber. The application of this sensor for internal crack detection of concrete beam has been demonstrated.

The continuous wavelet transform approach has been introduced in phase OTDR sensor system, which allows simultaneous detection of the frequency and time information for frequency of a few kHz at spatial resolution of 20cm over 1km sensing length. 10 vibration disturbances have been measured simultaneously for power generator monitoring.

9062-2

Improved distributed fiber optic sensing system based on single-ended double-pulse input Brillouin scattering

Tianying Chang, Ruijuan Yang, Jilin Univ. (China); Yongliang Wang, David Y. Li, L.C. Pegasus Corp. (China); Lei Jia, Shandong Univ. (China); Hong-Liang Cui, Jilin Univ. (China)

Distributed fiber optics sensing system based on Brillouin backscattered light can measure temperature and strain simultaneously, which generally has two types in structure. One is Brillouin optical time domain reflectometry (BOTDR), and the other is Brillouin optical time domain analysis (BOTDA). The former is single-ended input which is convenient for applications, but its spatial resolution is limited and the signal is week. The latter is double-ended input, which has opposite characteristics.

For BOTDR, input light's pulsewidth is one of the restraining factors for spatial resolution. Brillouin backscattered light is usually too weak to be detected if input light's pulsewidth is very narrow (less than 10ns). Therefore, spatial resolution of BOTDR is low (more than 1 m), because its input light's pulsewidth cannot be less than 10 ns. Based on the principle of Brillouin scattered light generation, single-ended double-pulse input is used to strengthen Brillouin backscattered light by increasing the population of acoustic phonons, which can be called improved BODTR. The first pulse which can be called the pump pulse, has a wide pulsewidth (tens or hundreds of microseconds) and is used to generate a nonlinear population of acoustic phonons in the sensing fiber. Whereas the second pulse which can be called the probe pulse, has a different central wavelength and a much narrower pulsewidth (several ns), and is emitted into the sensing fiber with a controlled time delay to absorb the generated abundant acoustic phonons, so that strong Anti-Stokes light can be generated. By detecting the intense Anti-Stoke light, whose frequency is related to the frequency of the probe pulse, Brillouin backscattered light in BOTDR can be detected easily, leading to high signal to noise ratio and better spatial resolution (less than 1 m), as well as good temperature and strain resolution, and longer sensing distance.

9062-3

Distributed fiber optic sensors for SHM: progress and needs *(Invited Paper)*

Katerina Krebber, Bundesanstalt für Materialforschung und -prüfung (Germany)

Distributed fiber optic sensors have proven to be an efficient and unmatched sensing tool for many applications. During the last decades, they have successfully moved from the laboratory to the field and have filled several application niches in the monitoring of geotechnical and civil infrastructures as well as of composite structures.

The lecture highlights the use of distributed fiber optic sensors based on silica and polymer optical fibers (Brillouin, OTDR, OFDR) for structural health monitoring in geotechnical and civil engineering as well as for the monitoring of composite structures. The results achieved in these fields in the framework of several German and European projects will be reviewed and the main challenges to these innovative fiber optic sensors will be addressed.

9062-4

Vibration pattern recognition and classification in OTDR based distributed optical-fiber vibration sensing system

Hui Zhu, Chao Pan, Xiaohan Sun, Southeast Univ. (China)

In the past decade varieties of OTDR based distributed optical fiber vibration sensing systems (DOFVS) were proposed with the functions of long range detection, multiple vibrations location and non-electromagnetic interference, and have been used in the areas of industries and perimeter security. However, a lot of researches about the current engineering systems fasten on the problem of the vibration location, ignoring the acquirement of vibration waveforms which are actually important signals for distinguishing the kinds produced by the vibration sources outsides. We demonstrate the scheme for both reproducing vibration waveform and locating in the OTDR based DOVFS in this paper.

A pulse light with repeat frequency f is injected into delay fiber and connection fiber through a 50:50 fiber coupler, and then another 50:50 fiber coupler is used to couple the two light beams into sensing fiber. With the help of differential detection of Rayleigh backscattering signals received from the first couple, multiple vibrations occurred synchronously can be monitored respectively and immediately. Detection module is designed, which can separate the signals received by the photodetector into vibration location pulses and vibration waveforms. Vibration waveforms are reproduced from the detecting pulses transmitted in which the original sensing signals have been included, by denoising selectively, adjusting bias voltage and band-pass filtering. The vibrations at the frequencies of 50Hz and 100Hz have been experimentally located and reproduced, respectively, and the highest frequency of 1 kHz for reproducing vibration waveform is realized with 2K repeat frequency of pulsed laser.

9062-5

Localized measurements of composite dynamic response for health monitoring *(Invited Paper)*

Kara J. Peters, Sean C. Webb, Kyle G. Oman, North Carolina State Univ. (United States)

We demonstrate that localized measurements of changes to the dynamic response of a composite structure can give accurate structural health monitoring at low damage levels. In particular, we demonstrate the detection and identification of realistic fatigue damage through embedded fiber Bragg grating sensors within the composite structure. Changes to the response of an aerospace composite structural component when subjected to a typical in-flight vibration spectrum are identified through the sensor dynamic signatures. The ability to multiplex several sensors is shown to enable detailed visualization of the local strain field and dynamic characteristics at the location of the sensor.

9062-6

Piezo-optical measurements for guided wave and acoustic emission structural health monitoring

Erik L. Frankforter, Bin Lin, Victor Giurgiutiu, Univ. of South Carolina (United States)

This paper presents the application and experimental validation of optical equipment suitable for high frequency guided wave and acoustic emission detection with fiber Bragg grating (FBG) sensors. The use of an acousto-ultrasonic FBG ring sensor to eliminate FBG directional dependence is also discussed. Guided wave and acoustic emission (AE) measurements were compared between piezoelectric wafer active sensors (PWAS) and FBG sensors embedded onto isotropic plates and beams with an emphasis on comparing frequency characteristics and noise levels. Low frequency guided waves were used to compare the frequency dependence of strain readings from PWAS at low frequencies. Since FBG sensors only detect strain longitudinal to the fiber, unlike PWAS they cannot serve as omnidirectional guided wave and AE sensors. To overcome this limitation, the use of an acousto-ultrasonic ring sensor, designed to augment and enhance the performance of FBG sensors, is discussed. The ring sensor used mechanical amplification principles to force in-plane vibration of the ring to occur at a specific resonance frequency. In this study, a ring sensor is bonded onto an isotropic plate; incoming guided wave and AE measurements from an FBG bonded to the ring sensor were compared to measurements from an FBG bonded to the plate. Preliminary results show the use of the ring sensor nearly eliminated the directional dependence of the FBG; concurrently the FBG on the ring sensor sensed incoming guided waves and AE events near its resonance frequency and rejected phenomenon occurring at other frequencies.

9062-7

Development of a plastic optical fiber and chemiluminescent crack detection sensor system for structural health monitoring

Kevin S. C. Kuang, National Univ. of Singapore (Singapore)

A sensor system has been developed based on the use of chemiluminescent material and plastic optical fiber (POF) to detect cracks in concrete structures. The sensing device, embedded in concrete beam specimens, is shown to be sufficiently sensitive to provide early warning of crack in concrete and has potential for application in structural health monitoring. In this study, a series of specimens with embedded sensors with different sensor configurations have been investigated and an assessment of their crack-detection capabilities will be reported. The specimens were tested under a three-point bend loading condition and the response of the sensor was recorded and corroborated with the physical response of the host specimen under failure load.

The paper will also reveal the initial results on the packaging of the sensor and it effectiveness of the proposed design for field application. A significant advantage of the system compared to previous work on the use of POF for crack-detection is that here the system does not require an electrically-powered light source and it will shown that crack detection can be achieved successfully via the embedded POF.

9062-8

Novel optical fiber ultrasonic sensor based on fiber laser

Qi Wu, Yoji Okabe, The Univ. of Tokyo (Japan); Junqiang Sun, Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology (China)

High-sensitive ultrasonic sensors are the fundamental device for effective ultrasonic non-destructive testing and health monitoring. Traditional PZT sensors suffer disadvantages including bulk size, brittle behavior and susceptibility of electromagnetic interferences. For solving these problems, we proposed and demonstrated a novel optical fiber ultrasonic sensor based on single longitudinal mode erbium fiber laser. An erbium doped fiber amplifier provided optical gain, and an apodized fiber Bragg grating and a fiber reflector constituted a linear cavity. A phase-shifted fiber Bragg grating (PS-FBG) with ultra-narrow transmitted peak was inserted into the linear cavity as a single longitudinal mode selector. The static performance of the laser was demonstrated by stable continuous wave output in time domain and single longitudinal mode oscillation in frequency domain. Then the dynamic performance of the sensor was evaluated through acousto-ultrasonic method on an aluminum plate. When only PS-FBG was glued on the plate, it acted as a punctiform sensor, similar to traditional FBG sensor. On the other hand, when the long lead single-mode fiber was glued on the plate, the sensor acted as a distributed sensor, detecting the ultrasonic wave along the fiber. These two sensing functions may be derived from different principles, which are Bragg wavelength shift and polarization vibration, respectively. According to our experimental results, this sensor has very high sensitivity, comparable to traditional PZT sensor. Furthermore, since the laser light was self-built, this sensor resisted to large temperature change. Moreover, this sensor has other advantages, such as low cost and simple configuration.

9062-9

Fluorescence monitoring with steering wheel photonic crystal fiber *(Invited Paper)*

Rosalind M. Wynne, Alpha Mansaray, Villanova Univ. (United States)

The development of a chemical sensor based on steering wheel photonic crystal fiber (SW-PCF) and a nanospectrometer chip form Nano-Optics Devices TM can benefit environmental sensing applictions. This chemical sensor can potentially result in a compact, image-based sensor with increased spectral resolution for applications such as environmental monitoring of water quality. A nanospectrometer is a planar spectrometer-on-chip that can be combined with a number of light sources. The chip diffracts incident light to a series of wavelength dependent spatially addressed dots that can be imaged and collected with a CCD camera. It is compact in size (10 mm x 15 mm x 0.5 mm) and has a high spectral resolution of 2x10-5um. This study is an extension of our previous investigation of water filled SW-PCF spectroscopy. Instead of analyzing water samples we tested flourescent dyes. Different types of dyes that absorbed and emmitted light in the same spectral window

as the chip were identified. The two dyes employed in this study are nile blue perchlorate and sulforhodimine 101. Spectroscopy measurements for nile blue perchlorate dye are presented in this conference paper.

We employed a 70 mW laser at 635nm to demonstrate the spectroscopsy capability of SW-PCF enhanced spectroscopy with a nano spectrometer. We demonstrated that the SW-PCF is suitable for spectroscopy of dyes with a conventional spectrum analyzer. A 5 microliter sample of dye was loaded into the 14cm long SW-PCF. We compared the spectroscopic data to an un-filled SW-PCF. Absorption was measured near 637nm and 638.5nm.

9062-10

Image-based spectroscopy for environmental monitoring

Rosalind M. Wynne, Eduard Bachmakov, Villanova Univ. (United States); Carolyn Molina, Villanova Univ (United States)

An image-processing algorithm for use with a nano-featured spectrometer chemical agent detection configuration is presented. The spectrometer chip acquired from Nano-Optic Devices can reduce the size of the spectrometer down to a coin. The nanospectrometer chip was aligned with a 635nm laser source, objective lenses, a length of steering-wheel photonic crystal fiber and a CCD camera. The images from a nanospectrometer chip were collected and compared to reference spectra. Random background noise contributions were isolated and removed from the diffraction pattern image analysis via a threshold filter. Results are provided for the image-based detection of the diffraction pattern produced by the nanospectrometer. The featured PCF/spectrometer configuration has the potential to measure optical absorption spectra in order to detect trace amounts of contaminants.

MATLAB tools allow for implementation of intelligent, automatic detection of the relevant sub-patterns in the diffraction patterns and subsequent extraction of the parameters using region-detection algorithms such as the generalized Hough transform, which detects specific shapes within the image. This transform is a method for detecting curves by exploiting the duality between points on a curve and parameters of that curve. By employing this image-processing technique, future sensor systems will benefit from new applications such as autonomous environmental monitoring of air or water quality.

9062-11

A novel microbending hetero-core fiber optic sensor for force and location sensing with applications to home security systems

Sumeyra Likoglu, Kubra Alemdar, Kemal Fidanboylu, Onur Toker, Fatih Univ. (Turkey)

In this paper, a novel design of microbending hetero-core fiber optic sensor for force and location sensing is proposed, and potential applications to home security systems is discussed. Force and location detection is done by using two different microbending fiber optic sensors. The main idea is, we have two unknowns, two different fibers, and two simultaneous intensity measurements. In order to demonstrate the location detection of the microbending fiber optic sensor, changes in the light intensity are examined with different force locations and forces magnitudes on the microbending fiber optic sensor. Several experiments are performed for different microbend sensors by varying periodicity, corrugation size, thickness of plates, and the configuration of optical fiber type. All experiments were done on a microbending sensor constructed from 62,5/125 and 50/125 μm multimode fibers and a microbending sensor constructed from 62,5-50-62,5/125 μm hetero-core fiber. For each case, the output light intensity is measured as a function of applied force. The characteristics of hysteresis, repeatability and location comparison are examined for each combination of microbending fiber optic sensors. . Experimental results show that the sensitivity of the proposed microbending sensor constructed using hetero-core optical fiber having loops is the highest.

9062-12

A novel periodic macrobending hetero-core fiber optic sensor embedded in textile for respiratory movements analysis

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This paper presents the design of a novel periodic macrobending hetero-core fiber optic sensor embedded in textile for respiratory movements analysis. We report on several different designs based on textiles which have different loop periodicity and configuration of optical fiber types. In all experiments, the changes of textile elongation are measured during breathing movements. In order to demonstrate the superiority of the proposed sensor, experiments were done on a macrobending sensor constructed from 62.5-50-62.5 hetero-core fiber and a macrobending sensor constructed from 62.5/125 μm multi-mode fiber having different loops. Experimental results show that the sensitivity of the proposed macrobending sensor constructed using hetero-core optical fiber is much higher than the sensor constructed from plain multi-mode optical fiber. It is also shown that, the sensitivity of the sensor increases as the number of loops is increased. On the other hand, several experiments were performed for periodic macrobending sensors having different bending radius by changing the lengths of loops amplitude and period. We demonstrate that the sensors tested on different patients' morphology can successfully sense respiratory movements.

9062-14

Millimeter-wave interferometry: an attractive technique for fast and accurate sensing of civil and mechanical structures

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Quick, accurate, and safe sensing of physical quantities or structures finds many applications and is of significant interest to society. Sensing using radio-frequency (RF) techniques, particularly, has gone through significant development and subsequently established itself as a unique territory in the sensing world. RF sensing has played a critical role in providing us many sensing abilities beyond our human capabilities, benefiting both civilian and military applications - for example, from sensing abnormal conditions underneath pavements and bridges, diagnosing them and imaging the defects, to measurement of displacement and detection of slow moving objects.

RF Interferometry is a phase-sensitive detection process, capable of resolving any measured physical quantity within a fraction of the operating wavelength. Interferometric sensor has relatively faster system response time than other sensors due to the fact that it is generally operated with a single-frequency source. RF interferometer is an attractive instrument for various engineering applications requiring fine resolution and fast response. It has been widely used for non-destructive material characterization, plasma diagnostics, position sensing, velocity profile, cardio pulmonary, radio astronomy, topography, meteorology, precision noise measurement, and displacement measurement.

We discuss the RF interferometry at millimeter-wave frequencies for sensing applications and report the development of millimeter-wave interferometric sensors. These sensors are completely realized using microwave integrated circuits. They have been used for various sensing including profile mapping and measurement of displacement. The sensors are capable of measuring accurately the surface topography of metal contours with 0.05 mm resolution. They also achieve a resolution and maximum error of only 10 um and 27 um, respectively, for displacement sensing. Quick response and accurate sensing, as demonstrated by the developed millimeter-wave interferometric sensors, make the millimeter-wave interferometry attractive for sensing of various civil and mechanical structures.

9062-40

Fiber optic temperature profiling for thermal protection system heat shields

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Reliable Thermal Protection System (TPS) sensors are needed to achieve better designs for spacecraft (probe) heat-shields for missions requiring atmospheric aero-capture or entry/reentry. In particular, they will allow both reduced risk and heat-shield mass minimization, which will facilitate more missions and allow increased payloads and returns. For thermal measurements, Intelligent Fiber Optic Systems Corporation (IFOS) is providing a temperature monitoring system involving innovative lightweight, EMI-immune, high-temperature resistant Fiber Bragg Grating (FBG) sensors with a thermal mass near that of TPS materials together with fast FBG sensor interrogation. The IFOS fiber optic sensing technology is highly sensitive and accurate. It is also low-cost and lends itself to high-volume production. Multiple sensing FBGs can be fabricated as arrays on a single fiber for simplified design and reduced cost. In this paper, we provide experimental results to demonstrate the temperature monitoring system using multi-sensor FBG arrays embedded in small-size Super-Light Ablator (SLA) coupon, which was heated towards the SLA charring temperature. In addition, a high temperature FBG array was fabricated and tested for 1000°C operation.

9062-15

Pulsed thermographic assessment of CFRP structures: experimental results and image analysis tools

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In this study, three different CFRP (Carbon Fiber Reinforced Polymer) specimens with internal artificial delaminations of various sizes and located at different depths were investigated by means of PT (Pulsed Thermography) under laboratory conditions. From the acquired results, it can be concluded that the implementation of PT along with the application of advanced signal processing algorithms can be a useful technique for NDT assessment, providing either enhanced qualitative information or quantitative estimations regarding the depth in which the feature of interest is detected. Despite the fact that PT is a fast and easy to deploy technique, unprocessed results can be easily affected by a series of different problems. Furthermore, although the raw thermal images can contain the complete information of the test material and can be used to detect delaminations, the thermal signatures of deeper features can be extremely small or undistinguishable from noise, especially when anisotropic materials have to be studied. The qualitative assessment of the three CFRP panels showed that techniques such as TSR (Thermographic Signal Reconstruction), PPT (Pulsed Phase Thermography) and PCT (Principal Component Thermography), can improve the visibility of the recorded pulsed thermographic signal and further enhance the thermal “footprints”, which is crucial in the case of deep and/or small defects. Additionally, by countering the problems affecting the raw temperature data, a greater amount of information can be retrieved with enhanced contrast and reliable quality. In other words, the algorithms used in this study were able to reduce the effects of uneven heating, significantly increasing the defect contrast and geometry representation while providing as well de-noised data (i.e. planar specimen analysis). Nevertheless, SNR (Signal-to-Noise Ratio) analysis showed that despite the enhanced visibility resulting from these algorithms, some observations can be made in order to gain the best possible information retrieval according to the user’s demands. More specifically, the 1st time derivative analysis and the PPT treatment of synthetic temperature data can provide better imaging results (higher SNR) for shallow defects with respect to the other processing routines used in this study. Additionally, PCT analysis produced also promising results as from the respective EOF (Empirical Orthogonal Functions) images it was possible to acquire the best possible information from deeper defects.

9062-16

Thermo-electrical Lockin thermography for characterization of subsurface defects

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In the present work, a novel method of infrared thermography called Thermo- Electrical Lockin thermography was developed for the characterization of subsurface defects in materials and structures. This new IR thermography method is based on the thermal excitation of materials under testing using a Peltier device and appropriate electronics allowing for accurate thermal cycling. Results from using this method were compared with different IR methodologies (i.e. Pulsed Phase thermography, Optical Lockin thermography), as well as ultrasonics. It was found that Thermo-Electrical Lockin thermography provides better resolution compared to the conventional NDE methods for characterizing subsurface defects in materials.

9062-17

Non-intrusive electric field sensing *(Invited Paper)*

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This paper presents an overview of non-intrusive electric field sensing. The non-intrusive nature is attained by creating a sensor that is entirely dielectric, has a small cross-sectional area, and has the interrogation electronics a long distance away from the system under test. One non-intrusive electric field sensing technology is the slab coupled optical fiber sensor (SCOS). The SCOS consists of an electro-optic crystal attached to the surface of a D-shaped optical fiber. It is entirely dielectric and has a cross-sectional area down to 0.3mm by 0.3mm. The SCOS device functions as an electric field sensor through use of resonant mode coupling between the crystal waveguide and the core of a D-shaped optical fiber. The resonant mode coupling of a SCOS device occurs at specific wavelengths whose spectral locations are determined in part by the effective refractive index of the modes in the slab. An electric field changes the refractive index of the slab causing a shift in the spectral position of the resonant modes. This paper describes an overview of the SCOS technology including the theory, fabrication, and operation. The effect of crystal orientation and crystal type are explained with respect to directional sensitivity and frequency response.

9062-18

Ion trap electrical field measurements using slab coupled optical sensors

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Ion traps use large electric fields to selectively isolate or "trap" ionized particles which can be mass-selectively ejected and analyzed. Characterizing the electric fields within the ion traps gives insight into their effectiveness in trapping and manipulating ions; however, measuring these fields with existing electric field sensors has not been feasible. Existing sensors are generally too large to fit within the compact spacing of the ion trap or their metallic composition perturbs the electric fields they are intended to measure. In this paper, we present a method for measuring electric fields in ion traps using sensors based on slab coupled optical sensor (SCOS) technology. SCOS are small, all-dielectric electric field sensors consisting of an electro-optic slab waveguide mounted to an optical fiber. Electric fields are measured by monitoring the coupling of light between the core of the optical fiber and the slab waveguide. These sensors exhibit a high level of single axis sensitivity along the optic axis of their slab waveguide allowing the sensor to distinguish both the amplitude and direction of an applied electric field. We demonstrate the functionality of SCOS for measuring fields within ion traps by characterizing the electric field profile of a coaxial ion trap. A coaxial ion trap contains a complex electrode structure which produces an electric field with components in both axial and radial directions to form multiple, linked trapping regions.

9062-19

High-speed non-intrusive high voltage measurement using slab coupled optical sensors

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High voltage measurements using optical fiber sensors offer significant bandwidth improvement compared to standard methods using voltage dividers. Besides, optical fiber sensor technology offers electrical isolation of the measurement equipment, making it safer to operate for both people and the equipment. We are using slab coupled optical fiber sensors (SCOS) in a parallel plate structure to measure high voltage. SCOS is an electric field sensor that works by coupling light from the fiber core into an electro-optic slab, which modifies the optical spectrum as a function of the applied electric field. SCOS is embedded in the dielectric within a parallel-plate electrode structure, used for voltage to electric field conversion due to its simple geometry. The electrode structure is optimized to minimize capacitance, prevent corona discharge and dielectric breakdown while maximizing the electric field between plates. Sub-millimeter SCOS dimensions allow reduction of plate area for achieving small electrode capacitance, which is essential for not perturbing the measured voltage. Corona discharge can also perturb the voltage due to dissipation of the charge from the system into the air. Corona discharge can be reduced by choosing proper electrode geometry and electrical insulation. We show how different electrode geometries have different corona discharges by measuring the UV light emission with a photodetector. Using the described SCOS electrode structure we measure a 500 kV 10 ns voltage pulse generated by a Marx generator. We suggest adjustments to the design parameters for measuring voltages up to 2 MV with bandwidth of 10 GHz.

9062-20

An ultrahigh sensitive self-powered current sensor utilizing a piezoelectric connected-in-series approach

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Recently, novel current sensors consisting of a magnet fixed on a piezoelectric-PZT beam are demonstrated to measure the magnetic-field produced by an AC current-carrying wire. The beam is deflected by the magnetic-force generated between the magnet and the magnetic-field. Due to the piezoelectric effect, the deflected beam produces a voltage-response. Hence, the beam's deflection-magnitude significantly influences the sensitivity of the sensors. To increase the sensitivity, the beam's resonant frequency has to be tuned to match the AC-current's frequency. However, even the frequency-matching is achieved to maximize the sensitivity, the current is difficult to be accurately measured when the magnitude-change of the current is undistinguished in some applications. Therefore, researchers are still searching an alternative approach to increasing the sensitivity. In this paper, we demonstrate a self-powered AC-current sensor using a piezoelectric connected-in-series approach to increase the sensitivity. The sensor consists of a CuBe-beam, piezoelectric-PZT-sheet, NdFeB hard-magnet, and mechanical-frame. When the sensor is placed in an alternative magnetic-field induced by an alternative current-carrying wire, the magnet fixed on the beam is subjected to an alternative magnetic-force between the magnet and magnetic-field. Thus, the beam is oscillated. Consequently, the piezoelectric-sheet fixed on the beam is periodically deformed and continuously produces voltage-response. When beams are connected in-series, the total voltage-response is significantly enlarged while the background-noise remains the same. The experimental result shows the voltage-response of the sensor consisting 10 beams connected in-series under the magnetic-field generated by a wire of 8-Ampere from a breaker is enlarged from 159 mV/A to 1272 mV/A.

9062-21

Structural health monitoring on turbine engines using microwave blade tip clearance sensors *(Invited Paper)*

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The National Aeronautics and Space Administration's (NASA) Aviation Safety Program (AVSP), is developing new sensor technologies and techniques for the in-situ structural health monitoring of gas turbine engines. As part of this program, microwave sensor technology is being investigated as a means of making high temperature non-contact tip clearance and tip timing measurements for use in structural health monitoring and active clearance control applications in gas turbine engines. This type of sensor has the potential to be highly accurate, able to operate in a high temperature environment, and not be affected by contaminants that are present in engines. The goal is to use blade tip clearance to monitor blade growth and wear and blade tip timing to monitor blade vibration and deflection. The use of microwave blade tip clearance sensors is an emerging concept. As a means of better understanding the issues associated with this type of sensor, several experiments have been conducted at the NASA Glenn Research Center to evaluate sensor performance on aero engine type applications. This included their use on a large scale Axial Vane Fan and a subscale Turbofan. More recently these sensors have been used to make crack detection measurements on sub scale turbine engine like disk. This paper presents a summary of key results and findings obtained from the previous evaluation experiments using the microwave sensors on the Axial Vane Fan and Turbofan, along with the results of the latest crack detection experiment that were accomplished on the subscale turbine engine disk.

9062-22

Turbine engine rotor health monitoring evaluation by means of finite element analyses and spin tests data

Ali Abdul-Aziz, Mark R. Woike, Michelle M. Clem, George Y. Baaklini, NASA Glenn Research Ctr. (United States)

Engine manufacturers are continuously striving to develop and design engine components that are efficient and successful in meeting flights safety and durability requirements. These development efforts are particularly focused on high speed rotating components such as rotor disks. Generally, these components undergo high rotational loading conditions which subject them to various types of failure initiation mechanisms. Therefore, to counter such design concerns; health monitoring of these components is a necessity and carrying out of such attribute is somewhat challenging to implement. This is primarily due to numerous factors and among them is the presence of scattered loading conditions, flaw sizes, and component geometry and materials properties which hinders the simplicity of applying such applications. Consequently, the need for advanced and applicable health monitoring techniques to monitor the performance of these rotating components is of essence. Nondestructive evaluation approaches are among the techniques being presently considered to pre-detect hidden flaws and mini cracks before any catastrophic event occurs. These methods or techniques extend more to assess materials' discontinuities and other defects that have matured to the level where a failure is likely.

This paper represent a summary work of combined experimental and analytical modeling that included data collection from a spin test experiment of a rotor disk at a rotational speed of up to 12,000 Rpm. It also covers presentation of results obtained from a finite element modeling study to characterize the structural durability of a cracked rotor as it relates to the experimental findings. The experimental data include blade tip clearance, tip timing measurements and shaft displacements. The tests are conducted at the NASA Glenn Research Center's Rotordynamics Laboratory, a high precision spin rig. The results are evaluated and examined to determine their significance on the development of a health monitoring system to pre-predict cracks and other anomalies and to assist in inaugurating a supplemental physics based fault prediction analytical model.

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9062-23

Progress of a cross-correlation based optical strain measurement technique for detecting radial growth of a rotating disk

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The Aeronautical Sciences Project under NASA's Fundamental Aeronautics Program is extremely interested in the development of novel measurement technologies that can be used to make optical surface measurements in the internal parts of a gas turbine engine. Gas turbine engines operate in severe environmental conditions and are therefore repeatedly exposed to high thermal and mechanical loads. The cumulative effects of these external forces lead to high stresses and strains on the engine components, such as the engine turbine disks, which may eventually lead to a catastrophic failure if left undetected. There are currently no in situ measurement techniques available to non-intrusively measure the strains experienced in the turbine engine and on its rotating components, including the turbine disk. Therefore, the development of measurement techniques in the form of new sensor technologies or methods for the in situ structural health monitoring of gas turbine engines and their components is of high interest to NASA. Currently, external sensors are under development at NASA Glenn Research Center including Microwave Blade Tip Clearance (MBTC)1-3 sensors and Capacitive Blade Tip Clearance (CBTC) sensors4. In addition to these external sensors, optical strain measurement techniques, such as using a Moiré Pattern5 are also being investigated. The current work presented in this paper expands upon a preceding study of a cross-correlation based optical strain measurement technique6 that offers potential fault detection by measuring the radial growth, which enables the calculation of strain, of an already cracked sub-scale engine turbine disk operating under loaded conditions. The optical strain measurement technique consists of imaging a high-contrast random particle pattern that is applied to an area of interest on the disk. Under loaded conditions, the disk experiences radial growth, thus causing the pattern to shift, i.e. creating a particle displacement. Images are acquired of the pattern before and after the shift and the resulting particle displacements are measured using 2D cross-correlation algorithms of Particle Image Velocimetry (PIV) software. Using PIV optimization guidelines, the initial proof-of-concept experiment in the preceding study evaluated several high-contrast random patterns and found a pattern consisting of retro reflective micro glass beads to be highly effective at detecting both experimentally and artificially induced shifts representative of the expected radial growth of the rotating disk. Continuing development of this optical strain measurement technique is presented. The retro reflective glass bead pattern is adhered directly onto a sub-scale engine turbine disk in the NASA GRC's High Precision Rotordynamics Lab and is used in several tests to further validate and better understand the limitations of this technique. The optical strain measurement technique is first used in a static test to experimentally measure thermal growth of the disk. Upon validation of the thermal growth measurement, it will be attempted to spin the disk at speeds up to 12000 rpm in an effort to detect strain experienced by the disk under loaded conditions. In addition, it is planned to compare the resulting radial growth detected by the optical strain measurement technique to finite element analysis and external sensor data.

9062-24

In-process, non-destructive multimodal dynamic testing of high-speed composite rotors

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Fiber reinforced plastic (FRP) rotors are lightweight and offer great perspectives in high-speed applications such as turbo machinery. Currently, novel rotor structures and materials are investigated for the purpose of increasing machine efficiency, lifetime and loading limits. Due to complex rotor structures, high anisotropy and nonlinear behavior of FRP under dynamic loads, an in-process measurement system is necessary to monitor and to investigate the evolution of damages under real operation conditions.

A non-invasive, optical laser Doppler distance sensor measurement system [1] is applied to determine the biaxial deformation of a bladed FRP rotor with micron uncertainty as well as the tangential blade vibrations at surface speeds above 300 m/s. The measurement system is applicable under vacuum conditions and offers a measurement rate above 10 kHz. Measurements at varying loading conditions are used to determine elastic and plastic deformations as well as hysteresis, fatigue, eigenfrequency shifts and loading limits. The deformation measurements show a highly anisotropic and nonlinear behavior and offer a deeper understanding of the damage evolution in FRP rotors.

The experimental results are used to validate and calibrate a simulation model of the deformation. It combines finite element analysis and a damage mechanics model. The combination of simulation and measurement system enables the monitoring and prediction of damage evolutions of FRP rotors in process.

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9062-25

The influence of fracture modes in acoustic emission signals in concrete beams

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The characterization of the dominant fracture mode may assist in the prediction of the remaining life of a concrete structure due to the sequence between successive tensile and shear mechanisms. Acoustic emission sensors record the elastic responses after any fracture event converting them into electric waveforms. The characteristics of the waveforms vary according to the movement of the crack tips, enabling characterization of the original mode. In this study fracture experiments on concrete beams are conducted. The aim is to examine the typical acoustic signals emitted by different fracture modes (namely tension due to bending and shear) in a concrete matrix. This is an advancement of a recent study focusing on smaller scale mortar and marble specimens. The dominant stress field and ultimate fracture mode is controlled by modification of the four-point bending setup while acoustic emission is monitored by six sensors at fixed locations. Conclusions about how to distinguish the sources based on waveform parameters of time (duration, amplitude) and frequency (peak frequency) domains are drawn. Specifically, emissions during the shear loading exhibit lower frequencies and longer duration than tensile. Results show that, AE helps to characterize the shift between dominant fracture modes using a simple analysis of few AE descriptors without the need for sophisticated pattern recognition analysis. This offers the basis for in-situ application provided that the distortion of the signal due to heterogeneous wave path is accounted for.

9062-26

A qualitative and quantitative investigation of the uncracked and cracked condition of concrete beams using impulse excitation, acoustic emission, and ultrasonic pulse velocity techniques

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The Impulse Excitation Technique (IET) is a useful tool for characterizing the structural condition of concrete In the present paper, five intact beams are examined, exhibiting a clear and systematic nonlinear behavior of the obtained damping ratio and frequency as a function of increasing response amplitude. Afterwards a mechanical load is monotonically or stepwise applied to all beams by means of three point bending tests leading to cracking. IET is again applied to the cracked beams indicating a damping ratio curve with much different tendency than the original. This implies that the shape of the curve can be used as a qualitative tool for the characterization of the state of concrete. It is also found that the shape of the nonlinear damping ratio curve remains similar for loading conditions below the ultimate level and for different measuring points across the central vertical line of the concrete beams. On the other hand, damping ratio and frequency values are influenced by age and maximum sustained load. Moreover, damping ratio measurements of the uncracked beams show a difference in the |(?min-?max)/?max| parameter ranging from 14 % to approximately 35 % . Additional information on the load of initial cracking, the accumulation rate of damage and the depth of the resulted crack is provided in real time for each loading step by Acoustic Emission (AE) and Ultrasonic testing which are complementary applied during the bending tests of the beams.

9062-27

Development of optical equipment for ultrasonic guided wave measurement

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This paper presents the development of optical equipment that is suitable for ultrasonic guided wave detection during active SHM in the hundreds of kHz range. In recent years, fiber Bragg gratings (FBG) have been investigated by several researchers as an alternative to piezoelectric sensors for the detection of ultrasonic waves. FBG have the advantage of being durable, lightweight, and easily embeddable into composite structures as well as being immune to electromagnetic interference and optically multiplexed. However, there is no commercially available product that uses this promising technology for the detection of ultrasonic guided waves because: (a) the frequency is high (hundreds of kHz); (b) the strains are very small (less than one microstrain); (c) the operational loads may also induce very large quasi-static strains (the superposition of very small ultrasonic strains and very large quasi-static strain presents a very significant challenge). Although no turn-key optical system exists for ultrasonic guided wave detection, we developed optical ultrasonic guided wave equipment using a tunable laser device. The measurement resolution and sampling speed were considered as the most important criteria in our test. We used two different configuration setups to achieve high sensitive (< 0.01 microstrain) and high sampling rate (> 30 MHz). Comparative measurements of low-amplitude ultrasonic waves were done including FBG, strain gauge, and piezoelectric wafer active sensors (PWAS). Calibration and performance improvements for the optical interrogation system are also developed and discussed. The paper ends with conclusions and suggestions for further work.

9062-28

Sensing light and sound velocities of liquids in two-dimensional phoxonic crystals

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During the past few years, there has been an increasing interest towards structures exhibiting simultaneous phononic and photonic band gaps, the so-called phoxonic crystals, thus allowing dual confinement of phonons and photons. From the point of view of sensing applications, several papers have already shown the capability of photonic crystals for detecting small variations in the refractive index of gases and liquids and have opened the way to a platform for a new class of sensors.
In contrast, phononic crystals have only been recently proposed as a possible platform for the investigation of the acoustic velocity of a liquid filling the hollow parts of the structure. In this work, we theoretically investigate the potentiality of different geometries of phoxonic crystals for a dual measurement of both acoustic and optical velocities of the analyte. We first study the transmission coefficient through a two-

dimensional (2D) crystal composed of a 2D infinite crystal made of air holes drilled inside a silicon matrix in which one row of holes is filled with a liquid. The conditions parameters of the cavity are discussed to define an optimized dual phononic photonic sensor for high and efficient acoustic and optical sensitivity. A second geometry is dealing with the case of alternating ridges and grooves on top of a thin Si membrane. The grooves can be filled with a liquid and the incident waves propagate parallel to the slab. Finally, we study the transmission normal to a silicon slab perforated periodically with holes.

9062-29

Elastic wave propagation on human femur tissue

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Cortical bone is one of the most complex heterogeneous media exhibiting strong wave dispersion. In such media when a burst of energy goes into the formation of elastic waves the different modes tends to separate according to the velocities of the frequency components as usually occur in waveguides. In this study human femur specimens were subjected to elastic wave measurements. The main objective of the study is using broadband acoustic emission sensors to measure parameters like wave velocity dispersion and attenuation. Additionally, waveform parameters like the duration, rise time and average frequency, are also examined relatively to the propagation distance as a preparation for acoustic emission monitoring during fracture. To do so, four sensors were placed at adjacent positions on the surface of the cortical bone in order to record the transient response after pencil lead break excitation. The results are compared to similar measurements on a bulk metal piece which does not exhibit heterogeneity at the scale of the propagating wave lengths. It is shown that the microstructure of the tissue imposes a dispersive behavior for frequencies below 1 MHz and care should be taken for interpretation of the signals.

9062-30

Ultrasonic guided wave sensing properties of PVDF thin film with inter digital electrodes

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Ultrasonic strain sensing performance of the large area PVDF with Inter Digital Electrode (IDEs) is studied in this work. Procedure to obtain IDE on a beta-phase PVDF is explained. PVDF film with IDE is bonded on a plate structure and is characterized for its directional sensitivity by determining the piezoelectric coefficient in various directions. Guided waves are induced to the IDE-PVDF sensor from different directions by placing a piezoelectric wafer actuator at different angles. Strain induced on the IDE-PVDF sensor by the guided waves in measured by using a Laser Doppler Vibrometer (LDV) and a wave propagation model. Using measured voltage response from IDE-PVDF sensor and the strain measurements from LDV the piezoelectric coefficient is estimated in various directions. Piezoelectric coefficient is estimated at various frequencies by varying the frequency of the guided wave launched by the piezoelectric waver actuator. A wider frequency band of operation is found by considering the variation in number of connected IDEs of the IDE-PVDF sensor. Thus variation in number of connected IDEs imparts the frequency tunable property to the IDE-PVDF sensor. The present study provides an effective technique to characterize thin film piezoelectric sensors for ultrasonic strain sensing at very high frequencies of 50-400 kHz. Often frequency of the guided wave is changed to alter the wavelength to interrogate damages of different sizes in Structural Health Monitoring (SHM) applications. An unique property of directional sensitivity combined with frequency tunability makes the IDE-PVDF sensor most suitable for SHM of structures.

9062-32

Infrared absorption enhancement phenomenon on nano materials

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The intensification of infrared-active vibrational modes of molecules in close proximity to nanometer-thick metal films, commonly known as surface-enhanced infrared absorption (SEIRA), is receiving increased attention from both a phenomenological and practical viewpoint. The resonant excitation of Plasmon in metallic nanostructures can provide large field enhancements on the surfaces of metals, which in turn provide dramatic increases in the detected spectroscopic signals for molecules adsorbed on their surfaces. The most widely used surface enhanced spectroscopy (SES) is surface enhanced Raman scattering (SERS), where the electromagnetic enhancement factor is proportional to the fourth power of the field incident on the molecule. Recently there has been a resurgence of interest in another type of SES, surface enhanced infrared absorption. It has been widely applied to surface trace analysis, bio-sensing, electro sorption, and electro catalysis because of its significant amplification of surface signal and simple surface selection rule. The surface enhanced infrared absorption can be observed easily on metal island films prepared by vacuum evaporation or sputtering and electrochemical or electroless deposition. Metal colloids also support the enhancement. Like surface-enhanced Raman scattering (SERS), SEIRA is chiefly of electromagnetic origin, that is, due to an increase in the local optical field exciting the adjacent molecule. Metal nano clusters much smaller than the wavelength of light facilitate the interaction of the infrared radiation with the metal and adsorbed molecules, resulting in the enhancement. It was explained that the enhancement is greatly affected by the size, and planer density of metal nano clusters compared with metal nano films. Phenomenological and theoretical difference of infrared absorption in broad ranges of wave length including near field to far field infrared rays between metal nano clusters and metal nano films. Especially, metal nano clusters exhibit much higher infrared absorption than metal nano films on broad ranges of wave length. The phenomenon of infrared absorption in the range of near infrared wave length was different from that of far infrared wave length. This different phenomenon involves shift of resonant peaks and absorption intensities on them. Also the planar density of the metal nano clusters suggests a mechanism to explain the phenomenon.

9062-33

3D mapping of reinforcement and tendon ducts on pre-stressed concrete bridges by means of ground penetrating radar (GPR)

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The inspection of reinforced and pre-stressed concrete bridges is a critical task and fundamental element continuing overall safety. Since the service life of those structures is mainly dependent on the normal age-related degradation and integrity loss of the embedded metallic reinforcement bars and tendon ducts, a detailed knowledge of the internal structural state is essential for the prevention of further damage and the improved planning of rehabilitation. Smart methods for assessing the structural integrity of such concrete bridges are therefore essential to ensure the safety, as well as to reduce the huge manufacturing costs and out of service time of the structure due to maintenance. Ground Penetrating Radar (GPR) is a well-established and among the leading diagnostic technologies in the field of NDT&E especially prepared for these purposes. The present study evaluates the potential of GPR for

the inspection of pre-stressed concrete bridges and its usefulness to provide non visible information of the interior structural geometry and condition required for strengthening and rehabilitation purposes. For that purpose, different concrete blocks of varying dimensions with embedded steel reinforcement bars, tendon ducts and fabricated voids, were prepared and tested by means of GPR in laboratory environment. 2D data acquisition was carried out in reflection mode along single profile lines of the samples in order to locate the internal structural elements. 3D surveys were also performed in a grid format both along horizontal and vertical lines, and the individual profiles collected were interpolated and further processed using a 3D reconstruction software in order to provide a detailed insight into the concrete structure. The obtained 2D profiles provided accurate depth and position of the embedded re-bars and tendon ducts verifying the original drawings. 3D data cubes were created enabling the presentation of depth slices and providing additional information such as shape and localization of the elements. The results obtained from this work showed the effectiveness and reliability of the GPR technique for pre-stressed concrete bridge investigations.

9062-34

Strength and fatigue life evaluation of composite laminate with embedded sensors

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Prognosis regarding durability of composite structures using various Structural Health Monitoring (SHM) techniques is important. Ultrasonic SHM systems with embedded transducers have potential due to their instant monitoring capability and eliminating various factors as compared to non-contact ultrasonic and eddy current techniques, which require disassembly of the structure. However, embedded sensors pose a risk to the structure by acting as a flaw thereby reducing life. The present paper focuses on the determination of strength and fatigue life of the composite laminate with embedded film sensors like CNT nanocomposite, PVDF thin films and piezoceramic films. First, the techniques of embedding these sensors in composite laminates is described followed by the determination of static strength and fatigue life at coupon level testing in Universal Testing Machine (UTM). Failure mechanisms of the composite laminate and embedded sensors are studied for static and dynamic loading cases. The coupons are monitored for loading and failure using embedded sensors. Using the response from these sensors, various stages of loading and failure mechanisms can be monitored. Using fracture mechanics models, a life prediction strategy is proposed for the cases of static and dynamic loading. A comparison of the performance of these three types of embedded sensors is made to study their suitability in various applications. These three types of embedded sensors cover a wide variety of applications, and prove to be viable in embedded sensor based SHM of composite structures.

9062-35

Flexoelectric micro acoustic transducer using barium strontium titanate

Seol Ryung Kwon, Wenbin Huang, Fuh-Gwo Yuan, Xiaoning Jiang, North Carolina State Univ. (United States)

Flexoelectric acoustic transducers using barium strontium titanate ($Ba_{0.65}Sr_{0.35}TiO_3$ or BST) ceramic were investigated in this study. Bridge and cantilever shaped acoustic transducers with dimensions of 1.5 mmx768 ?mx50 ?m were fabricated using micro-machined BST ceramics. The prototyped transducers were installed in an anechoic box and exposed to the sound pressure emitted from a loud speaker. The output charge from both types of transducers was measured and their sensitivities were compared. Calculated sensitivities were found to be 1.02 pC/Pa for the bridge transducer and 10.59 pC/Pa for the cantilever transducer while their resonance frequencies were calculated to be 98.67 kHz and 15.51 kHz, respectively. The analytical and experimental results show that the flexoelectric acoustic transducer has high sensitivity to the sound pressure and high resonance frequency, implying that flexoelectric acoustic transducers are potential candidates for cochlear-like acoustic sensors with higher sensitivity than piezoelectric counterparts.

9062-36

A new molecular dynamic model of nanowire

Lin Wang, Longqiu Li, Guangyu Zhang, Hongguang Xu, Qian Sun, Harbin Institute of Technology (China)

Man-made nanomotor is an amazing object that can perform various tasks and diverse applications, such as, delivering drugs to cancer cells, nanoscale cargo transport and so on.

In this paper, a model based on a chemically powered nanowire is established. The motion of the nanowire has been simulated using a mesoscopic hybrid molecular dynamics-multiparticle collision (MD-MPC) dynamics method. The effect of the ratio between catalytic and non-catalytic segment, which is an interested problem, is analysed. The length and radius of the model are changed to discuss their effect on the center-of-mass velocity of the nanowire along its axis. The temperature and the solvent concentration on the nanowire motion have been researched respectively.

9062-37

The damage assessment methodology in cooperation with smart sensors and inspection robots

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For the damage assessment system, the power consumption issue is of importance to transmit the measured data to data storages. Wireless communication devices, which are usually employed for a data transmission, require a large amount of power. The infrared data transmission using the infrared LED is one of the solutions for power consumption.

This paper proposes a damage assessment methodology in cooperation with smart sensors and inspection robot. The smart sensor unit for the proposed system consists of microcontroller and sensors. The unit also uses the infrared LEDs in sending the measured data to the inspection robot. The inspection robot integrated in the proposed system has a wireless camera and infrared remote control receiver for receiving the data from smart sensor. The inspection robots will be able to estimate the damage condition without any process of engineers' on-site-inspection involved.

In the proposed methodology, the distributed smart sensors firstly detect the damage and its location. Next, the robots can gather the data from the smart sensor units, which transmit the measured data by using infrared remote control receiver and LED signal. The robot also can inspect the damage location and captures the photographic image of the damage condition.

For demonstrating the feasibility or possibility of the proposed damage assessment, the laboratory experiment of is conducted. From the experimental result, the developed damage assessment methodology in cooperation with smart sensor and inspection robot has a capability of providing valuable information for the repair and maintenance decision making of a damaged structure.

9062-38

Cheap optical transducers (CHOTs) as chemical sensors

Theodosia Stratoudaki, Leonel Marques, Matthew Clark, Mike G. Somekh, The Univ. of Nottingham (United Kingdom)

CHeap Optical Transducers (CHOTs) are a new breed of ultrasonic transducers that are optically activated for generation and detection of ultrasonic signals. CHOTs offer a range of advantages over the traditional contact piezoelectric transducers: wireless, remote, reliable, couplant free operation. They are activated by light, with a great potential of becoming inexpensive to manufacture so as to be considered as disposable or be used in large numbers.

CHOTs are 2-D patterns of nanometre height, attached on a substrate such as a glass coverslip and are optically excited by means of lasers for generation and detection of acoustic waves, including surface acoustic waves (SAWs). There is a CHOT for generation (g-CHOT) and a CHOT for detection (d-CHOT). The two can be used as a coupled system or separately to either generate or detect ultrasound. We have previously demonstrated CHOTs' potential in Non Destructive Testing where they can be used to detect defects in industrial components. The present paper demonstrates the CHOTs capabilities as SAW chemical sensors. Experiments are presented where CHOTs are used to measure the thickness of a gold layer and preliminary results for substance identification on polymers. It is anticipated that these preliminary results will pave the way for the application of CHOTS in the healthcare monitoring market, food and environmental industry.

9062-39

Thermal and electrical behavior of nano-modified cement mortar

Dimitrios A. Exarchos, P. Dalla, Konstantinos G. Dassios, Theodoros E. Matikas, Univ. of Ioannina (Greece)

No Abstract Available

9062-41

Fiber-optically sensorized composite wing

Joannes Costa, Richard J. Black, Behzad Moslehi, Levy Oblea, Vahid Sotoudeh, Intelligent Fiber Optic Systems Corp. (United States); Essam Abouzeida, Vladimir Quinones, Yasser Gowayed, Paul Soobramaney, George Flowers, Auburn Univ. (United States)

Light-weight, electromagnetic interference (EMI) immune fiber-optic sensor based Structural Health Monitoring (SHM) will play an increasing role in aerospace structures ranging from aircraft wings to jet engine vanes. Intelligent Fiber Optic Systems Corporation (IFOS) has been developing multi-functional fiber Bragg grating (FBG) sensor systems including parallel processing FBG interrogators combined with advanced signal processing for SHM, structural state sensing and load monitoring applications. This paper reports work with Auburn University on embedding and testing FBG sensor arrays in a quarter scale model of a T38 composite wing. The wing was designed and manufactured using fabric reinforced polymer matrix composites. FBG sensors were embedded under the top layer of the composite. Their positions were chosen based on strain maps determined by finite element analysis. Static and dynamic testing confirmed expected response from the FBGs. The demonstrated technology has the potential to be further developed into an autonomous onboard system to perform load monitoring, SHM and Non-Destructive Evaluation (NDE) of composite aerospace structures (wings and rotorcraft blades). This platform technology could also be applied to flight testing of morphing and aero-elastic control surfaces.

9062-42

Lamb wave-based damage detection of composite shells using high-speed fiber-optic sensing

Vahid Sotoudeh, Richard Black, Behzad Moslehi, Intelligent Fiber Optic Systems Corp. (United States); Pizhong Qiao, Washington State Univ. (United States)

A Lamb wave-based damage identification method called damage imaging method for composite shells is presented. A damage index (DI) is generated from the delay matrix of the Lamb wave response signals, and it is used to indicate the location and approximate area of the damage. A piezoelectric actuator is employed to generate the Lamb waves that are subsequently captured by a fiber Bragg grating (FBG) sensor element array multiplexed in a single fiber connected to a high-speed fiber-optic sensor system. The high-speed sensing is enabled by an innovative parallel-architecture optical interrogation system. The viability of this method is demonstrated by analyzing the numerical and experimental Lamb wave response signals from laminated composite shells. The technique only requires the response signals from the plate after damage, and it is capable of performing near real-time damage identification. This study sheds some light on the application of a Lamb wave-based damage detection algorithm for curved plate/shell-type structures by using the relatively low frequency (around 100 kHz) Lamb wave response and the high-speed FBG sensor system.

9062-43

Fast fiber Bragg grating interrogation system with scalability to support monitoring of large structures in harsh environments

Behzad Moslehi, Joannes Costa, Richard J. Black, Vahid Sotoudeh, Intelligent Fiber Optic Systems Corp. (United States)

Fiber optic sensor systems can alleviate certain challenges faced by electronics sensors faced when monitoring structures subject to marine and other harsh environments. Challenges in implementation of such systems include scalability, interconnection and cabling. We describe a fiber Bragg grating (FBG) sensor system architecture based that is scalable to support over 1000 electromagnetic interference immune sensors for harsh environment applications. A key enabler is a high performance FBG interrogator supporting subsection sampling rates ranging from kHz to MHz. Results are presented for fast dynamic switching between multiple structural sections and the use of this sensing system for dynamic load monitoring as well as the potential for acoustic emission and ultrasonic monitoring on materials ranging from aluminum and composites to concrete subject to severe environments.

9062-44

Thermal diffusivity of templated nanocomposite using frequency modulated infrared imaging

Lalat Indu Giri, Suneet Tuli, Indian Institute of Technology Delhi (India)

The present study reports thermal diffusivity measurement of anodic alumina (AAO) templated bismuth telluride nanowires using recently proposed frequency modulated thermal wave imaging (FMTWI). The technique provides a fast and efficient non-contact approach for in-plane thermal characterization of a nonmaterial. A frequency modulated (up-chirp) signal is applied as photothermal excitation to the sample, and the thermal response is monitored using an infrared (IR) thermography based temperature sensing system. Thermal diffusivity of the sample is experimentally assessed using the multiple phase information extracted from a single run of the experiment. This feature considerably reduces the operational time of the experiment as compared to similar lock-in thermography based approaches. This unique approach of solely using the phase information for thermal diffusivity measurements, allows the experiment to be more immune to the local variations in surface temperature and emissivity of the radiating surface. The theoretical background and experimental details of the technique are discussed, with practical measurement of thermal diffusivity of Bi_2Te_3/AAO nanocomposite in direction perpendicular to the channel axis.

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9063-1

New strategies for SHM based on a multichannel wireless AE node *(Keynote Presentation)*

Valery F. Godinez-Azcuaga, Obdulia Lay, MISTRAS Group, Inc. (United States)

This paper discusses the development of an Acoustic Emission (AE) wireless node and it application for SHM. Originally planned for applications in steel and concrete bridges components, the initial prototypes were also used in monitoring composite wind turbine blades and composites mockups of Unmanned Autonomous Vehicles (UAV) components. The final product, now commercially available, is a sensor node which includes multiple sensing elements, on board signal processing and analysis capabilities, signal conditioning electronics, power management circuits, wireless data transmission element and energy harvesting unit. The sensing elements are capable of functioning in both passive and active modes, while the multiple parametric inputs are available for sensors to measure external characteristics affecting the performance of the structure under monitoring. The output of all these sensors are combined and analyzed at the sensor node in order to minimize the data transmission rate, which consumes significant amount of power. Power management circuits are used to reduce the data collection intervals through selective data acquisition strategies and minimize the sensor node power consumption. This instrument, known as the 1284, is an excellent platform to develop SHM not only in the original bridge applications but also in fields such as coal flow, power transformer, and off-shore platform monitoring. This project was sponsored by the National Institute of Standards and Technology of the USA through the Technology Innovation Project Grant #70NANB9H007.

9063-2

Studying the effect of cracks on the ultrasonic wave propagation in a two-dimensional gearbox finite element model

Didem Ozevin, Hossein Fazel, Univ. of Illinois at Chicago (United States); Justin Cox, William Hardman, Naval Air Warfare Ctr. Aircraft Div. (United States); Seth S. Kessler, Metis Design Corp. (United States); Alan Timmons, Naval Air Warfare Ctr. Aircraft Div. (United States)

Gearbox components of aerospace structures are typically made of brittle materials with high fracture toughness, but susceptible to fatigue failure due to continuous cyclic loading. Non-destructive evaluation methods are used to monitor the crack growth in gearbox components. Damage detection methodologies developed in laboratory-scale experiments may not represent the actual gearbox structural configuration and are usually not applicable to real application as the vibration and wave properties depend on the material, structural layers and thicknesses. Also, the sensor types and locations are key factors for frequency content of ultrasonic waves. which are essential features for pattern recognition algorithm development in noisy environments. Therefore, a deterministic damage detection methodology that considers all the variables influencing the waveform signature should be considered in the preliminary computation before any experimental test matrix. In order to achieve this goal, we developed a two dimensional finite element model of a gearbox cross section. It consists of steel revolving teeth, a thin layer of oil, retention plate and housing. A wave is generated by one sensor and received by the other one in various conditions. The baseline data includes the case that there are no cracks in the teeth. Various crack positions with specified width in one of the teeth are simulated. The received waveforms are compared; so, we are able to analyze the effect of the crack on the wave propagation in gearbox. Having known this effect, damages can be detected at early stages and sudden failures will be prevented.

9063-3

Assessment of weld quality of aerospace grade metals by using ultrasonic matrix phased array technology

Jeong K. Na, Edison Welding Institute (United States)

A nondestructive weld quality characterization methodology based on the matrix phased array (MPA) ultrasonic technology has been developed and tested on aerospace grade alloy materials such as aluminum, titanium and stainless steels. The purpose of this effort is to replace the time consuming destructive testing, which involves sectioning, etching and measuring the fused part of the weld. Currently, this destructive testing process has to be conducted every so often during production to ensure the quality of welds in the aerospace parts and components. Various plate samples made by two of the most common welding techniques, resistance spot welding and resistance seem welding, have been prepared and tested. The inspection results not only include the image of welds but also give size and area of fused section of the part. In this study, detailed discussions are made for the newly developed MPA imaging methodology as well as test results of various welded test coupons are shown. Based on the current results, it is promising that the MPA ultrasonic imaging inspection method has a high potential to replace the time consuming destructive testing process.

9063-4

3D-assisted defect recognition for the ultrasonic waveform inspection of titanium components

Andrew Ferro, Patrick Howard, GE Aviation (United States)

Titanium aircraft engine forgings are inspected at all material depths using the ultrasonic testing (UT) process called multizone inspection. This process creates a raster array of 1D A-scan signals that image the material's underlying characteristics, which in the case of forged titanium, result in highly variable noise. The 3D volume is analyzed as a stack of 2D depth slices that are gated into C-Scans. The intention is to accept or reject the part by examining for the presence of small anomalies in these images in terms of their signal to noise ratio (SNR). Ultrasonic testing inspectors determine that rejection decision by using specialized image software and a 2D assisted defect recognition (ADR) algorithm. This approach for calculating SNR greatly reduces inspector subjectivity compared to a manual approach, but in 2D, not all available information is used to determine a true detection. Enabling ADR to use the 3D volume for the forging inspection, an automated SNR calculation has been extended to address these issues. The 3D ADR algorithm's life cycle from design to validation will be discussed. Validation testing

results have shown that 3D ADR significantly increases probability of detection compared to 2D ADR while also reducing its false positive rate.

9063-5

Ultrasonic sensor for thickness measurement of hybrid materials

Marc C. Wurz, Anja Wienecke, Lutz Rissing, Jens Twiefel, Jörg Wallaschek, Leibniz Univ. Hannover (Germany)

To investigate hybrid materials (material sandwiches consisting of at least two different material layers) and to determine layer thickness without sample destruction, different methods exist. Most common strategies are eddy current, thermographic, radiologic and ultrasonic approaches.

To measure a wide range of layer thicknesses at high temperatures and without much safety concern, the ultrasonic method is the most promising approach.

This paper visualizes the development concept for a micro ultrasonic sensor for thickness measurement of hybrid materials.

To generate ultrasonic waves existing methods, magnetorestrictive, piezo-electric, and laser are considered. Special attention is paid to their applicability under high temperatures. For magnetorestrictive transducers NiFe 45/55 and CoFe (different composition) are investigated. For piezo-electric transducers gallium orthophosphate and lithium niobate with temperature stability up to 900°C are taken into consideration. Furthermore, link gels which can be used under high temperatures are examined. Despite the selection of appropriate materials to generate the sensor effect, their integration in an applicable system offers another area of research.

9063-6

Crack propagation testing using a YCOB acoustic emission sensor

Joseph A. Johnson, Kyungrim Kim, North Carolina State Univ. (United States); Shujun Zhang, The Pennsylvania State Univ. (United States); Xiaoning Jiang, North Carolina State Univ. (United States)

Piezoelectric crystals are popular for passive sensors, such as accelerometers and acoustic emission sensors, due to their robustness and sensitivity. These sensors are widespread in structural health monitoring among civil and industrial structures, but there is little application in nuclear reactor structures due to the few materials that are capable of operating at elevated temperatures. Most piezoelectric materials suffer from a loss of electric properties above temperatures in the 500-700°C range, but rare earth oxyborate crystals, such as Yttrium calcium oxyborate (YCOB), retain their piezoelectric properties above 1000 °C. Sensors with this high temperature capability are increasingly needed as existing nuclear facilities continue to age up to and past their initial 40-year license. Our previous research demonstrated that YCOB can be used to detect transient lamb waves via Hsu-Nielsen tests, which replicate acoustic emission waves, up to 1000°C. In this paper, YCOB piezoelectric acoustic emission sensors will be tested for their ability to detect crack progression at elevated temperatures. The sensor was fabricated using a YCOB single crystal and Inconel electrodes and wires. The sensor was mounted onto a stainless steel bar substrate, which was machined to include a pre-crack notch. A dynamic load was induced on the bar with a shaker in order to force the crack to advance along the width of the substrate. Wavelet analysis software was used to predict the Lamb wave frequency characteristics, and the raw data was processed and analyzed in the frequency domain.

9063-7

Two-year corrosion monitoring of prestressed concrete piles using acoustic emission

William Vélez, Fabio Matta, Paul H. Ziehl, Univ. of South Carolina (United States)

Corrosion of bonded steel strands in prestressed concrete (PC) piles in seawater prompts major concerns on the service life of bridges along coastlines. The concurrent and cyclic exposure to moisture, chlorides and oxygen at the intertidal zone facilitates early corrosion of the prestressed steel reinforcement. Corrosion effects in multi-wire strands can be exacerbated by crevice corrosion at the wire impingement sites, and presence of prestressing forces. These effects can result in earlier and more severe corrosion in prestressed strands than in adjacent non-prestressed bars and stirrups, and are more difficult to recognize through traditional half-cell potential measurements. It is desirable to assess corrosion in a nondestructive fashion before serviceability and safety are compromised.

This paper reports on an ongoing research to investigate acoustic emission (AE) for the remote monitoring of corrosion in PC piles. Earlier laboratory investigations on corrosion in PC structures have been based on accelerated techniques that make it difficult to faithfully mimic actual corrosion processes. The results presented herein cover two years of AE monitoring of five PC pile specimens exposed to wet-dry salt water cycles simulating tidal action. Benchmark half-cell potential and polarization resistance measurements were taken to recognize the onset and progression of corrosion. Visual evidence was obtained from corroded strands extracted from selected specimens after halting testing at different times after corrosion initiated. The results served to define tentative quantitative criteria for corrosion assessment using AE intensity analysis. In addition, AE noise filtering and its effect on the intensity analysis results are discussed.

9063-8

Accurate pupil function applied quantitative evaluation of materials with scanning acoustic microscopy

Seon Hee Kim, Seoul National Univ. of Science and Technology (Korea, Republic of); Jeong Nyeon Kim, The Pennsylvania State Univ. (United States); Dong Ryul Kwak, Seoul National Univ. of Science and Technology (Korea, Republic of); Richard L. Tutwiler, The Pennsylvania State Univ. (United States); Ikkeun Park, Seoul National Univ. of Science and Technology (Korea, Republic of)

Scanning acoustic microscopy (hereinafter simply called “SAM”) is an acoustic imaging technique used for characterizing materials.

The Pupil function is an integral part of the V(z) curve calculation which is the output voltage signal of the SAM. This formulation is based on the angular-spectrum (Fourier-optical) method. In previous research, these equations We have been simplified to model the reflection of the acoustic field (ie. both inside the lens aperture, and outside).

In this study, to find the accurate reflected field distribution of surface acoustic waves, the complex pupil function has been simulated. The acoustic lens model used in the development of the simulation is a conventional acoustic lens configuration. The Pupil function in the new model integrates the complex pressure at each focal point. These results were compared with those modeled using simplified pupil and calculations based upon experimental data. Application of a more accurate representation of the pupil function was shown to improve the V(z) simulation of the acoustic field.

9063-9

High frequency elastic wave propagation in large structures using spectral elements and perfectly matched layer

Zahra Heidary, Didem Ozevin, Univ. of Illinois at Chicago (United States)

The influence of mechanical noise in an Acoustic Emission (AE) testing still obscures its successful application in monitoring various structures and systems. While advances in pattern recognition algorithms are helpful to differentiate relevant data from captured noise, the algorithms fail if the characteristics of relevant data are unknown. A better scientific understanding of the characteristics of elastic waves due to damage mechanisms in a structure is needed for developing a quantitative measurement approach of damage (e.g. frequency content, type, orientation) based on the AE method. The results of small scale coupon tests cannot be directly used in large scale structures due to the influence of boundaries on propagating waves detected by the AE sensors. In this paper, a steel plate is modeled using an absorbing boundary condition and spectral elements in order to understand the direct wave release from damage without influenced by reflections. The selected absorbing layer is perfectly matched layer (PML), which is designed such a way that wave reflections from boundaries back into the solution domain regardless of frequency or angle of incidence are prevented through providing a stable solution and satisfying the Sommerfeld radiation condition. The displacement-based and time-domain equations of PML are utilized. The numerical results of the two-dimensional metal plate with absorbing boundary condition are validated with extended-geometry numerical models and experimental results.

9063-10

Evaluation of induction healing performance of asphalt mixtures with ultrasonic scattering and mechanical measurements

Qingli Dai, Zigeng Wang, Michigan Technological Univ. (United States)

This paper is to investigate the induction healing performance of electroactive asphalt concrete beam samples with ultrasonic scattering and mechanical measurements. The electrically conductive steel wool fibers were mixed with asphalt materials to heat the surrounding binders through induction energy. By introducing Newtonian binder flow in the heated asphalt materials, the microcrack healing performance can be significantly improved with the accelerated process. To investigate the induction healing performance, asphalt concrete beam samples were prepared by incorporating Type 1 steel wool fibers with an approximate length of 6.5 mm. The asphalt mixture beams were tested with fracture-healing cycles using the modified three-point bending test with an elastic foundation support and healing procedure. Prior to the fracture tests, both samples were conditioned in the freezer for 6 hours at -20oC to limit the viscoelastic and unrecovered deformation. The peak loading values were recorded to study the induction healing effects. In addition, the ultrasonic scattering techniques will be developed for determining the pore size distribution inside asphalt mixture samples. The measurements before and after induction healing will be used to evaluate the repaired microcrack distribution inside the samples.

9063-11

Acoustic and temperature-based non-destructive testing for damage assessment of concrete masonry system subjected to seismic loading

Md Fuad H. Khan, Ivan Bartoli, Satish Rajaram, Prashanth Abraham Vanniamparambil, Antonios Kontsos, Mohamad Bollhassani, Ahmad Hamid, Drexel Univ. (United States)

This paper represents a hybrid non-destructive testing (HNDT) approach based on infrared thermography (IRT), acoustic emission (AE) and ultrasonic (UT) techniques for effective damage quantification of partially grouted concrete masonry wall (CMW). This advanced inspection approach is powerful and has the potential to be implemented for the health monitoring of concrete masonry system (CMS). The implementation of this hybrid system assists the cross validation of in situ recorded information for structural damage assessment. In this context, non-destructive testing was performed on a partially grouted concrete masonry wall subjected to cyclic loading using MTS actuators. Among these three different NDT techniques, the acoustic emission (AE) and Infrared thermography (IRT) images have been recorded during each cycle of loading while the ultrasonic (UT) hammer test has been performed in between each cycle. Four accelerometers, bonded at the toe of the wall, were used for recording waveforms from both active and passive acoustic approach. A high frequency sonic stress waves were generated by an instrumental hammer and the corresponding waveforms were recorded by the accelerometers. The obtained IRT, AE and UT results exhibited the internal structural health condition and accumulated progressive damage throughout the loading history. Detailed post-processing of these results was performed to characterize the defects at the region of interest. The obtained experimental results already demonstrate the potential of the method to detect flaws on monitored specimens; further experimental investigations are planned towards the quantitative use of these NDT methods.

9063-12

Characterization of complex materials with elastic discontinuities using scanning acoustic microscope

Xin Li, Richard L. Tutwiler, The Pennsylvania State Univ. (United States)

Joint materials are widely used in various fields of industry. To non-destructively evaluate the multilayer structured in a thin film system, the mechanical scanning acoustic reflection microscope (hereinafter simply called “SAM”) is utilized and the V(z) curve method is used to characterize the mechanical structure characteristics of the system.

In this study, V(z) curve simulation software is developed to simulate the voltage output signal of SAM to model the elastic discontinuities on the sample surface. The calculation is based on the angular-spectrum method in conjunction with a ray-optic approximation. A pupil function splitting method is also used in this calculation. The pupil function is split into two parts according to the position of the discontinuity within the specimen.

To examine the reliability of the simulation, several real measurements are made using a specimen consisting of a laser joint SPCC and SUS block, and the results are compared with the simulation results. The procedure will use SAW velocities of the specimen measured from different locations. And the measured results are compared with calculated result using the simulation software. Suitable metrics are used to illustrate that the simulation approximates the real data collection within a suitable error tolerance.

9063-13

Monitoring the fracture behavior in ceramic matrix composites by infrared thermography and acoustic emission

Dimitrios A. Exarchos, Konstantinos G. Dassios, Theodoros E. Matikas, Univ. of Ioannina (Greece)

In this work an innovative methodology was employed for monitoring the fracture behavior in silicon carbide fiber-reinforced ceramic matrix composites. This new methodology was based on the combined use of IR thermography and acoustic emission. Compact tension SiC/BMAS specimens were tested with unloading/reloading loops and the thermal dissipation due to crack propagation and other damage mechanisms was monitored by IR thermography. The accuracy of this technique was benchmarked by optical measurements of crack length. In addition, using acoustic emission descriptors, such as activity during the unloading part of the cycles, provided the critical level of damage accumulation in the material. Acoustic emission allowed to closely following the actual crack growth monitored by IR thermography, enabling quantitative measurements.

9063-14

Influence of geometry on the fracturing behavior of textile reinforced cement monitored by acoustic emission

Dimitrios G. Aggelis, Johan Blom, Vrije Univ. Brussel (Belgium); Michael Elkadi, Jan Wastiels, Vrije Univ Brussel (Belgium)

The textile reinforced cement composite (TRC) used in this study is a combination of inorganic phosphate cement (IPC) with random distributed glass fibres. IPC has been developed at the “Vrije Universiteit Brussel” and shows a neutral pH meaning that glass fibers are hardly attacked. Textile reinforced cement exhibits high strength and ductility and thus provides a new material for thin shells with high resistance to high temperature, and no production of toxic gasses.

In this work the flexural behavior of the laminate is examined using acoustic emission (AE). During bending, stresses lead to the activation of damage mechanisms like matrix cracking, delamination’s and fiber pull-out being in succession or overlapping in time. AE records the responses of the damage propagation events and allows the monitoring of the fracture behavior from the onset to the final stage. Different geometry aspects are examined, namely the length and thickness of the plates, as well as their curvature in arch-shaped specimens.

AE is used to determine the onset of damage while location is used to examine the influence of the beam shape to the fracture process zone. Parameters like duration and frequency reveal information about the mode of the damage sources in relation to the curvature. Results show that as the curvature increases, the dominant mode shifts away from bending and acquires more shear characteristics increasing the delamination events. This is confirmed by finite element stress analysis on the structures. Simultaneous wave velocity measurements enable information on the stiffness degradation relatively to the load

9063-15

Towards early ice detection on wind turbine blades using acoustic waves

Viktor Berbyuk, Bo Peterson, Jan Möller, Chalmers Univ. of Technology (Sweden)

During cold weather operation of wind turbines ice easily adheres to the turbine blades causing maintenance challenges impacting their normal operation and during extreme icing conditions even causing shut down or prolonged periods of inactivity. The present research is carried out at the division of Dynamics, Chalmers University of Technology aiming to quantify the position and the type of the ice buildup at an early exposure phase minimizing the downtime period of the cold weather operation of wind turbines. The project is supported by the Swedish Wind Power Technology Centre and is part of its research program. The study focuses on the early detection of ice build using magnetostrictive controlled acoustic waves propagating in the turbine blades. An experimental set-up with a cold climate chamber, composite test object used in turbine blades and equipment for glaze and rime ice production has been developed. The propagation of three orthogonally polarized acoustic waves was studied by means of 6 accelerometers positioned, 3 each, in 2 holders at approximately 0.4 m from each end of the 8 m long test object. The composite material in the test object is the same as normally used in wind turbine blades. The obtained results show that the formation of ice, the ice mass, icing areas and the temperature have a significant influence on guided wave propagation w.r.t. Fourier transform, amplitude attenuation and RMS values as indicators. There is no significant damping in the material that has been tested concluding that the proposed acoustic wave technique is a promising approach for ice detection.

9063-16

Framework and implementation of a continuous network-wide health monitoring system for roadways *(Keynote Presentation)*

Ming L. Wang, Ralf Birken, Salar Shahini Shamsabadi, Northeastern Univ. (United States)

According to the 2013 ASCE report card America’s infrastructure scores only a D+. There are more than four million miles of roads (grade D) in the U.S. requiring a broad range of maintenance activities. The nation faces a monumental problem of infrastructure management in the scheduling and implementation of maintenance and repair operations, and in the prioritization of expenditures within budgetary constraints. The efficient and effective performance of these operations however is crucial to ensuring roadway safety, preventing catastrophic failures, and promoting economic growth. There is a critical need for technology that can cost-effectively monitor the condition of a network-wide road system and provide accurate, up-to-date information for maintenance activity prioritization.

The Versatile Onboard Traffic Embedded Roaming Sensors (VOTERS) project provides a framework and the sensing capability to complement periodical localized inspections to continuous network-wide health monitoring. Research focused on the development of a cost-effective, lightweight package of multi-modal sensor systems compatible with this framework. An innovative software infrastructure is created that collects, processes, and evaluates these large time-lapse multi-modal data streams. A GIS-based control center manages multiple inspection vehicles and the data for further analysis, visualization, and decision making. VOTERS’ technology can monitor road conditions at both the surface and sub-surface levels while the vehicle is navigating through daily traffic going about its normal business, thereby allowing for network-wide frequent assessment of roadways. This deterioration process monitoring at unprecedented time and spatial scales provides unique experimental data that can be used to improve life-cycle cost analysis models.

9063-17

A new vision of the post-NIST civil infrastructure program: the challenges of next-generation construction materials and processes

H. Felix Wu, Yan Wan, Univ. of North Texas (United States)

Our nation's infrastructural systems are failing every day. The deterioration process grows over time. The physical aging of these vital facilities and the remediation of their current critical state pose a key societal challenge to the U.S. Current sensing technologies, while well developed in controlled laboratory environments, have not yielded tools for producing real-time, in-situ data that are comprehensible for infrastructure decision-makers. The need for advanced sensing technologies is national because every municipality and state in the nation faces infrastructure management challenges. The need is critical because portions of infrastructure are reaching the end of their life-spans and there are few cost-effective means to monitor infrastructure integrity and to prioritize the renovation and replacement of infrastructure elements. New advanced sensing technologies that produce cost-effective inspection and real-time monitoring data, and that can also help or aid in meaningful interpretation of the acquired data, therefore will enhance the safety of the public in regard to structural integrity by issuing timely and accurate alert data. New advanced sensing technologies also allow more informed management of infrastructural investments by avoiding premature replacement of infrastructure and identifying those structures in need of immediate action to prevent from catastrophic failure. Infrastructure management requires that once a structural defect is detected, an economical and efficient repair be made. Advancing the technologies of repairing infrastructure elements in contact with water, road salt, and subjected to thermal changes requires innovative research to significantly extend the service life of repairs, lower the costs of repairs, and provide repair technologies that are suitable for a wide range of conditions. All these new technologies will provide increased lifetimes, security, and safety of elements of critical infrastructure for the Nation's already deteriorating civil infrastructure. It is envisioned that the Nation should look far beyond: not only we will efficiently and effectively address current problems of the aging infrastructure, but we must also further develop next-generation sustainable construction materials and processes for new construction. To accomplish, this ambitious goal, we must include process efficiency that will help select the most reliable and cost-effective materials in construction processes; performance and cost will be the prime consideration for selecting construction materials selected based on life-cycle cost and materials performance; energy efficiency will drive reduced energy consumption from current levels by 50% per unit of output; and environmental responsiveness will achieve net-zero waste from construction materials and its constituents. Should it be successfully implemented, we will transform the current 21st century infrastructure systems to enable the vital functioning of society and improve competitiveness of the economy to ensure that our quality of life remains high.

9063-18

Evaluating pavement surface conditions using dynamic tire pressure sensor

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In order to best prioritize road maintenance, the level of deterioration must be known for all roads in a city's network. Pavement Condition Index (PCI) and International Roughness Index (IRI) are two standard methods for obtaining this information. However, IRI is substantially easier to measure. Significant time and money could be saved if a method were developed to estimate PCI from IRI. This research introduces a new method to estimate IRI and correlate IRI with PCI. A vehicle-mounted dynamic tire pressure sensor (DTPS) system is used. The DTPS measures the signals generated from the tire/road interaction while driving. The tire/road interaction excites surface waves that travel through the road. DTPS, which is mounted on the tire's valve stem, measures tire/road interaction by analyzing the pressure change inside the tire due to the road vibration, road geometry and tire wall vibration. The road conditions are sensible to sensors in a similar way to human beings in a car. When driving on a smooth road, tire pressure stays almost constant and there are minimal changes in the DTPS data. When driving on a rough road, DTPS data changes drastically. IRI is estimated from the reconstructed road profile using DTPS data. In order to correlate IRI with PCI, field tests were conducted on roads with known PCI values in the city of Brockton, MA. Results show a high correlation between the estimated IRI values and the known PCI values, which suggests that DTPS-based IRI can provide accurate predictions of PCI.

9063-19

Pavement macrotexture estimation using principal component analysis of tire/road noise

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This work presents a method for pavement macrotexture depth (MTD) estimation using measurements from a microphone mounted underneath a moving vehicle. Such measurements will include tire-generated sound, which carries much information about the road condition, as well as noise generated by the environment and vehicle. The proposed method uses Principal Component Analysis (PCA) to differentiate important information about the road surface from noisy data while vehicle is moving. The analysis begins with acoustic pressure measurements made over constant and known road conditions. Fourier transforms are taken over various time windows and a PCA is performed over the resulting vectors, yielding a set of principal component vectors for that road condition. Each road condition is characterized by a set of principal component vectors. The integration of the sound pressure of the first principal component vector over the frequency range 40 to 700 Hz is computed as the energy reflecting macrotexture depth. A model developed from Taylor expansion is built to predict MTD from the computed PCA energy and the driving speed. Successful applications of this method are demonstrated by accurate estimations of the mean texture depth (MTD) of pavement directly from acoustic measurements.

9063-20

DCPD resins for concrete pavement pothole patching materials

Wei Yuan, Jenn-Ming Yang, Kuo-Yao Yuan, Univ. of California, Los Angeles (United States)

Not unique to asphalt pavement, Portland concrete pavement also develops potholes from cracks and craters. Currently, the asphalt materials are widely used to fix potholes in concrete pavement. Due to the durability problem of those asphalt materials and the heavy traffic on concrete pavement, those asphalt repairs easily fail, and their service life is short. We employed our DCPD approach combined with asphalt materials to tackle the concrete pavement distresses. In this proceeding, we characterized the increased bonding strength between asphalt materials and concrete pavement with the help of DCPD resin infiltration. A push-out test was used to characterize the DCPD edge bonding to the concrete. By designing some locking (caging) structures (such as trench), the low viscosity DCPD resin can infiltrate into the concrete and form a strong ribbon to firmly lock up the filled materials. With the highly rutting

resistance, improved interface bonding, and caging structure design, the concrete pavement pothole could be well repaired with prolonged service time.

9063-21

Air-coupled ultrasonic system for fusion of impact-echo tests and surface wave measurements

Seong-Hoon Kee, Nenad Gucunski, Rutgers, The State Univ. of New Jersey (United States)

The main objective of this study is to develop a prototype air-coupled ultrasonic system (ACUS) for simultaneous data collection of impact-echo tests and surface wave measurements in concrete bridge decks. The ACUS includes two hexagonal air-coupled sensor arrays, each of which includes a solenoid-driven impact source at the center and six air-coupled sensors (ACSs) with parabolic acoustic reflectors (PARs) at vertices of a hexagon. The developed ACUS will be used as a part of an automated nondestructive evaluation and rehabilitation system (ANDERS) for concrete bridge deck inspection. First, a prototype hexagonal ACS array with PARs was developed in laboratory, and the prototype ACUS was built by combining the two hexagonal ACSs in a row. Second, an advanced data interpretation and visualization algorithm for the ACUS was developed for presenting the resulting data from individual test method, and data fusion of the two methods. Third, acoustic scanning was conducted using the developed ACUS over a simulated concrete bridge deck having various artificial defects (delaminations, surface-breaking cracks, segregated aggregates, partially grouted tendon ducts, and accelerated corrosion test regions). The results were visualized as several defect maps (i.e., frequency map and energy map from the IE testing, and velocity and transmission map from the surface wave measurements). In addition, the images from the two different test methods were combined by using a proposed fusion algorithm. It will be demonstrated that the ACUS is very effective for improving speed of data collection, and that the innovative fusion algorithm enables more accurate data interpretation.

9063-22

Automatic road markings recognition development

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Road surface markings provide guidance and information to drivers, promote road safety, and ensure the smooth flow of traffic. Most previous studies in this area focused on the detection and recognition of lane lines with very limited prior work on the recognition of lane center road markings. This paper focuses on the development of algorithm for automatically detecting and recognizing road markings of patterns and word messages at traffic lane center. Road markings of Chinese characters are firstly studied. In addition, a method for identifying the completeness of road markings is also presented. Authors propose an approach to extract road marking features based on the derivation of a binary matrix image transformed from laser reflectance collected from a top down roadway view laser scanner. The results of case studies (city streets) show that the approach can detect and recognize lane center road markings with a significant success rate. The average success rate is 96.06%, 94.05%Chinese character road markings and 97.73% direction arrows and others. From the case studies, it was also noted that a significant portion of road markings have relatively low completeness. Further studies will focus on increasing survey speed, detecting other highway classes containing different Chinese characters and road markings, increasing detection rate, and developing a decision making strategy for road marking maintenance.

9063-23

Clogging evaluation of porous asphalt concrete in conjunction with medical x-ray computed tomography

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This study was to assess the porosity of Porous Asphalt Concrete (PAC) in conjunction with a medical X-ray computed tomography (CT) facility. The PAC was designed as the surface course to achieve the target porosity 18%. There were graded aggregates, soils blended with 50% of coarse sand, and crushed gravel wrapped with geotextile compacted and served as the base, subbase, and infiltration layers underneath the PAC. The test section constructed in 2004 is located at an agency branch in Northern of Taiwan in which the daily traffic by the vehicles owned by agency staff has been light and limited. The porosity of the test track was investigated. The permeability coefficient of PAC was found severely degraded from 2.2”?” 10-1cm/sec to 1.2”?” 10-3cm/sec, after nine-year service, while the permeability below the surface course remained intact. Several field PAC cores were drilled and brought to evaluate the distribution of air voids by a medical X-ray CT nondestructively. The helical mode was set to perform the X-ray CT scan and two dimensional virtual slices were exported in seconds for analyzing air voids distribution. It shows that the clogging of voids occurred merely 20mm below the surface and the porosity can reduce as much about 3%. It was also found that the roller compaction can decrease the porosity by 4%. The permeability reduction in this test site can attribute to the voids of PAC that were compacted by roller during the construction and filled by the dusts on the surface during the service.

9063-24

Repair monitoring of cracked concrete floor using the impulse response method

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The objective of the present study was the repair monitoring of an extensively cracked concrete floor using the Impulse – Response method. The study included the evaluation of the condition of the concrete floor that suffered from extensive cracking on its surface, through systematic tests. The purpose of the study was to investigate the causes that led to extensive cracking on the floor surface in order to plan the repair strategy. The investigation included a thorough visual inspection and recording of cracks, estimation of the crack depth using ultrasonic pulse velocity measurements, investigation for voids between the concrete floor and the underlying aggregate layer using the Impulse – Response method, concrete floor thickness estimation using the Impact – Echo method and concrete quality estimation using cores cutting. The repair method that was chosen was based on grout injections in order to fill the voids located between the concrete and the underlying aggregate layer. The area, where the injections took place, was inspected using the Impulse – Response method before and after the injections for monitoring purposes and a secondary grid was designed after considering the results. The area was inspected for a third time, after injecting in the secondary grid, in order to confirm the successful filling of the voids.

9063-25

Modelling ultrasound guided wave propagation for plate thickness measurement

Rakesh Malladi, Rice Univ. (United States) and Texas Instruments Inc. (United States); Anand G. Dabak, Nitish K. Murthy, Texas Instruments Inc. (United States)

Structural Health monitoring refers to monitoring the health of plate-like walls of large reactors, pipelines and other structures in terms of corrosion detection and thickness estimation. The objective of this work is modeling the ultrasonic guided waves generated in a plate. The piezoelectric is excited by an input pulse to generate ultrasonic guided lamb waves in the plate that are received by another piezoelectric transducer. In contrast with using finite element modeling or pattern recognition algorithms, we develop a mathematical model of the direct component of the signal (DCS) recorded at the terminals of the piezoelectric transducer. The DCS model uses maximum likelihood technique to estimate the different parameters, namely the time delay of the signal due to the transducer delay and amplitude scaling of all the lamb wave modes due to attenuation, while taking into account the received signal spreading in time due to dispersion. The maximum likelihood estimate minimizes the energy difference between the experimental and the DCS model-generated signal. We demonstrate that the DCS model matches closely with experimentally recorded signals and that it can be used to estimate thickness of the plate. The main idea of the thickness estimation algorithm is to generate a bank of DCS model-generated signals, each corresponding to a different thickness of the plate and then find the closest match among these signals to the received signal, resulting in an estimate of the thickness of the plate. Therefore our approach provides a complementary suite of analytics to the existing thickness monitoring approaches.

9063-26

Vibrational characteristics of FRP-bonded concrete interfacial defects in a low frequency regime

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As externally bonded fiber-reinforced polymer (FRP) is a critical load-bearing component of civil infrastructures, the betterment of structural health monitoring (SHM) methodology for such composites is imperative. Henceforth the vibrational characteristics of near surface interfacial defects involving delamination and trapped air pockets at the FRP-concrete interface are investigated in this study using a finite element approach. Intuitively, due to its lower interfacial stiffness, a defective region is expected to have a set of resonance frequencies different from an intact region when excited by acoustic waves. Indeed, it has been observed in our model that, no matter excited by a single impulse, a transient exposure to a sinusoidal wave of a single frequency, or a steady-state frequency sweep, both the vibrational amplitudes and frequency peaks in the response spectrum of the defects demonstrate a significant deviation from an intact FRP-bonded region. For a thin sheet of FRP bonded to concrete with sizable interfacial defects, the fundamental mode under free vibration is shown to be relatively low, in the order of kHz. Due to the low vibrational frequencies of the defects, the use of low-cost equipment for interfacial defect detection via response spectrum analysis is shown to be feasible.

9063-27

Feasibility study on 3 axis magnetic sensor for flux leakage method

Akira Sasamoto, National Institute of Advanced Industrial Science and Technology (Japan)

Most of NDT system by magnetic field sensing has employed coil or semiconductor as sensor which has one axis sensitivity. Recent development of semiconductor technology can makes a chip that enable us to measure 3 axis magnetic field in a 1mm square.

This vector information is expected to show a new insight in NDT testing.

This presentation will show a basic experimental feasibility study for application of magnetic sensor to flux leakage and eddy current testing method by using a sensing system with the chip.

9063-28

Estimation performance of civil structures from impulse response data: graph interpretation

Gopichand Movva, Shuo Sun, Yan Wan, H. Felix Wu, Univ. of North Texas (United States)

Wireless sensor networks have been widely used to monitor the health of civil structures. Rich data have been collected, however how to interpret such data to understand the health of civil structures and how to better design data collection experiments to improve the quality of data remain to be challenging. In this paper, we explore the problem of using impulse response-type sensor measurement data to infer the health of civil structures. In particular, actuation impulse is applied to certain location in a structure, and vibration response data are measured at another location. From the vibration response data, we infer key parameters of the structure. Such inference can be formulated as an estimation problem from impulse response data, with the dynamics of structure formulated as a second-order differential equation. The performance of such inference is highly dependent upon the locations of sensors and the topology of the structure, which can be represented as a graph underlining the damping and stiffness matrices. In this paper, we characterize the estimation performance from the topological graph of these two matrices, using a unique approach that meshes graph theory, control theory, and estimation theory. The expected results on the direct relationship between graph structures and the estimation performance of key structural parameters will contribute to both structural engineering and control theory in that: estimation methods in structural engineering typically ignores the damping matrix, and in control engineering graphical results on estimation performance have only been studied for systems with first-order dynamics.

9063-29

The extended Ibrahim time-domain modal identification method for over-damped structural systems

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In the previous study, the conventional Ibrahim time-domain method (ITD) using free-decay responses of structures has been extensively used in the modal-identification analysis, however, which is only applicable to identify the modal parameters of an under-damped structure. In the present paper, we propose a theoretical modification for ITD method, and extended the ITD method for modal identification of over-damped structural systems. Numerical simulations confirm the validity of the

proposed method for modal identification of over-damped structural systems.

9063-30

Dynamic monitoring of stay cables by enhanced cable equations

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In a typical vibration test of tensioned cables, tension forces are mostly estimated from theory of a vibrating string with the first natural frequency. To obtain slightly better estimations, formulas based on an axially loaded beam can be employed. However, uncertainty on both flexural rigidity and effective length of the vibrating cable raise difficulty in reliably determining the possible range of the tension value. From the previous work of the authors, an enhanced approach for the calculation of tension forces without the need of rigidity data had been proposed, in which frequencies of high modes are instead required in recovering accurate results. This paper extends the previous work to also consider the discrepancy between the design length and effective length so as to further improve the results.

Current study aims to apply the proposed approach to the dynamic monitoring of the in-situ stay cables so as to improve the traditional assessment results without increasing the testing costs. Ambient dynamic responses obtained by accelerometers and Remote microwave interferometry will be cross examined. Expected outcome will include the verification of the proposed methodology by actual cable forces measured in a newly erected cable-stayed bridge.

9063-31

Matrix crack detection in spatially random composite structures using fractal dimension

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Vibration based method is one of the methods commonly used to detect damage in composite structures. But in the case of large structures such as an aircraft wing or a bridge, it is preferable to use static response based damage detection than vibration based method. It is easier to extract static response than dynamic characteristics such as frequencies, mode shapes and damping factors.

In this paper, Fractal Dimension (FD) based damage detection method is proposed to detect localized damage in a composite plate from static response data. Matrix cracking is considered as damage in the composite plate as it is often seen as initial damage mechanism in composite structures. Finite element method is used to model a cantilevered composite plate with localized matrix cracks. A uniform load is applied to the cantilevered plate with damage and static deflection is recorded. Area of the damage considered here is 4% of the total plate area, which is considerably small compared to the total plate area. The static deflection of damaged plate is compared with undamaged plate and it is found that, there is no substantial change in static deflection due to damage. The static response data is processed using FD to extract the damage.

It is found that the FD based method is able to detect single and multiple damage locations from static deflection. To study the effectiveness of the proposed method in a random material properties scenario, composite material properties are assumed as two-dimensional random field. Static deflection is calculated for composite plate with spatially varying material properties and damage. It is found that FD based method is able detect damage location in a composite plate with spatially varying random material properties.

9063-75

Acoustic metamaterial with negative parameter

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In this paper we present experimental and theoretical results on an acoustic metamaterial that exhibits negative effective mass and negative effective stiffness. A one-dimensional acoustic metamaterial with an array of spring-mass subsystems in a bar was fabricated. The frequency characteristics of the acoustic metamaterial has the same form as that of the permittivity in metals due to the plasma oscillation. We also provide a theory to explain the simulation results. And numerical simulations reveal that the actual working mechanism of the proposed metamaterial bar is based on the concept of conventional mechanical vibration absorbers. It uses the incoming elastic wave in the bar to resonate the integrated spring-mass-damper absorbers to vibrate in their optical mode at frequencies close to but above their local resonance frequencies to create shear forces and bending moments to straighten the beam and stop the wave propagation. Moreover, we design a finite periodic system composed of such basic units to confirm that the modeling and analysis techniques are available.

9063-76

Disbond detection using guided wave pzt excitation in honeycomb composite sandwich structure

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This research study is motivated to overcome the short-comings of the conventional health monitoring techniques and proposes the new technique for the in-situ structural health monitoring without disassembling the structure. The semi-analytical method based upon global matrix approach is used to study the dispersion characteristics of the Honeycomb Composite Sandwich Structure (HCSS). The specimen transversely isotropic HCSS plate is modeled and analyzed for various load cases using this technique and compared these results with a similar HCSS model developed using Finite Element based software LS-DYNA. The results are found in excellent agreement for the developed HCSS models. The time domain signals with respective wavelet transforms are used to study the Guided Wave interaction in the disbonded HCSS model. This study investigated the A0 mode reflection from the exit of the disbond for vertical narrow band PZT Excitations. Whereas, the change in amplitude and phase difference of few wave modes are observed for horizontal narrow band PZT Excitations at various receiver locations. From this research study, it is entrusted that the developed technique may find its place as promising in-situ health monitoring technique for HCSS.

9063-77

SHM-based condition assessment of expansion joints in suspension bridges

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Expansion joints are important components in bridges, which are subject to various loads including wind, temperature and vehicle pounding impact. Premature failures of modular expansion joints were found in Jiangyin Yangtze river suspension bridge and Runyang Yangtze river suspension bridge. In order to diagnose damage of expansion joints, measurements from Structural Health Monitoring System of two

suspension bridges are analyzed.

A procedure is firstly proposed to evaluate health condition of expansion joints with girder temperature and girder-end longitudinal displacement measurements. Condition assessment of expansion joints is conducted, which indicates good correlation between effective girder temperature and cumulative girder-end longitudinal displacement. In order to further investigate causes for the damage, displacements between suspension bridges and cable-stayed bridges are compared. The result shows large discrepancy of cumulative girder-end longitudinal displacement in two types of bridges. Excessive cumulative longitudinal displacement and collision by passing vehicles are found to be main reasons for damage of expansion joints in suspension bridges.

Based on the study, specific countermeasures are proposed to improve the performance and extend the service life of large-displacement expansion joints, which include using high wear-resistant slider material in expansion joints, additional displacement-constraint device and fluid girder damper. The proposed countermeasures were applied to Jiangyin Yangtze River Highway Bridge and Runyang Yangtze River Highway Bridge. Measurements of longitudinal displacement show large decrease in both cumulative displacement and largest displacement under vehicle pounding impact.

9063-78

Assessment of bond defects in adhesive joints before and after the treatment with laser generated shock waves

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An improper pre-treatment of surfaces with low adhesive properties and / or skin formation on the bead of the adhesive during adhesive application can result in a total decrease in adhesive strength, although a molecular contact exists between adhesive and adherent. This so called kissing bond effect is generally not detectable with conventional nondestructive testing because kissing bonds behave very similar to an intact adhesive. The lack of accurate methods for the detection of these defects is one of the reasons that prevent the wider use of adhesive bonding in aeronautical or automotive industry. A promising way is the approach, that kissing bonds show a typical behavior under a specific load. High power compression waves, shearing forces or a simple mechanical tensile loading can transfer the kissing bond state into a gap debonding state. Therefore, one has to apply a suitable method such as loading the adhesive joint using laser-generated shock waves in order to make this kind of defect detectable. The present work describes the results of experimental studies on nondestructive inspection of flaws in bonded joints of metal materials. While it is not the purpose of this work to evaluate or characterize shock waves, we demonstrate that kissing bond flaws can be made visible nondestructively using laser-generated shock waves.

9063-79

Research progress of highway disease detection based on acoustic emission

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Because of the long-term overload, highway could be unsafe. The life and use of the highway will be seriously affected. As a kind of real-time dynamic monitoring technology, Acoustic Emission is a non-destructive testing. The testing technology only displays and records the extensional defects. So it has been widely used in terms of engineering structure health detection. In this paper, the present situation of acoustic emission detection in engineering structure and highway is summarized. It refers to the application of acoustic emission in the geologic, and then the parameters of the structure acoustic emission detection is determined. At the same time, according to the structure characteristics and the optimization methods, the sensors are better arranged for evaluating the disease in the structure. Acoustic Emission testing is used to detect the engineering structure, and then the defects can be effectively located. It will provide some important information for the use and maintenance of engineering structure.

9063-80

Evaluating cover depth of steel fiber reinforced concrete using impact-echo testing

Yu Feng Lin, Chienkuo Technology Univ. (Taiwan)

The purpose of this research is to estimate of the cover depth of the reinforced concrete using the impact-echo testing. In order to evaluate the security of the construction, usually need to estimate the cover depth of the reinforced concrete. At present, the examination technique of the cover depth of the reinforced concrete without the steel fiber is mainly applied in the magnetic and electrical methods, its rapid detection and good results. But the research of the reactive powder concrete be gradually progress, with the steel fiber concrete structure will be increased, if should still operate the examination with the magnetic and electrical methods, theoretically the steel fiber will have the interference to its electromagnetism field. Therefore, this research designs four kinds of reinforced concrete plate that include different steel fiber contents, to evaluate test results of estimate of the cover depth of the reinforcing bar. The results showed that: estimate of the cover depth of the reinforcing bar using the impact-echo testing, the variety of the steel fiber content does not have much influence, all test measurement error within ± 8%, and the most important source of uncertainty is the velocity of concrete.

9063-83

Application of focused schlieren towards seedless velocimetry measurements

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Seedless velocimetry has been implemented to several flow fields to perform quantitative velocity measurements typically accomplished with the implementation of particle image velocimetry (PIV). PIV is a well-established and heavily applied fluid flow measurement method. PIV allows for both two and three component planar measurements which are achieved by imaging small particles that are assumed to faithfully follow the flow. However, introduction of seed particles can be problematic in many cases. In this work, seedless velocimetry is achieved by imaging the naturally occurring turbulent eddies using the focusing Schlieren (FS) measurement system. The 2 component velocity vectors are computed using traditional cross-correlation routines.

9063-85

Structural health monitoring in composite stiffened panels using ERA/NExT

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In order to ensure safe use of composite structures, Non-Destructive Inspection (NDI) and Structural Health Monitoring (SHM) play a very crucial role to identify damage. NDI is an offline approach of damage detection, which involves significant economic costs due to the frequent grounding of aircraft, shutdown time, and labour involved in inspections.

Therefore, continuous health monitoring of the composite structures are needed to identify damage before occurrence of catastrophic failure using minimal time and human interventions. Composite stiffened panels are used in many structures especially in ship, aircraft, and pressure vessel, due to their simplicity in fabrication and excellent stiffness. This research focus on a cost effective and reliable SHM technique for composite stiffened panels using system identification based on Eigen Realisation Algorithm (ERA). A methodology has been developed to extract stiffness values of stiffened panel; this methodology worked on System Identification (SI) technique based on Eigen Realization Algorithm (ERA) integration with Natural Excitation Technique (NExT). These stiffness values are used to identify location and severity of the damage in composite stiffened panels from naturally excited time domain data. The proposed methodology was applied for both numerical and experimental analysis to identify location and severity of damage in different test cases of composite stiffened panels with delamination of different sizes and locations. A very good agreement of result was found in all test cases for assessing the size and location of damage using numerical and experimental analysis.

9063-86

Investigations of moisture ingressions in composite panels via NDI techniques

Raghavendra Salagame, Vamsidhar R. Patolla, Ramazan Asmatulu, Wichita State Univ. (United States)

No Abstract Available

9063-87

Guided wave phased array sensor tuning for improved defect detection and characterization

Jason H. Bostron, Joseph L. Rose, The Pennsylvania State Univ. (United States)

Ultrasonic guided waves are finding increased use in a variety of Nondestructive Evaluation and Structural Health Monitoring applications due to their efficiency in defect detection using a sensor at a single location to inspect a large area of a structure and an ability to inspect hidden and coated areas for example. With a thorough understanding of guided wave mechanics, researchers can predict which guided wave modes will have a high probability of success in a particular nondestructive evaluation application. For example, in a sample problem presented here to asses bond integrity, researchers may choose to use a guided wave mode which has high in-plane displacement, stress, or other feature at the interface. However, since material properties used for modeling work may not be precise for the development of dispersion curves, in many cases guided wave mode and frequency selection should be adjusted for increased inspection efficiency in the field. In this work, a phased array comb transducer is used to sweep over phase velocity – frequency space to tune mode excitation for improved defect characterization performance. A thin coating layer bonded to a thick metal structure is considered with a contaminated surface prior to bonding. Physically-based features are used to correlate wave signals with defect detection. The features assessed include arrival time, apparent frequency shift, various amplitude and area ratios in time and frequency domain, and others. Excellent results are obtained.

9063-32

Cyber-enabled wireless monitoring systems for the health management of bridges: a retrospective summary of technology development and field validation *(Keynote Presentation)*

Jerome 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 a 5 year research and development effort undertaken at the University of Michigan, in collaboration with commercial partners, focused on the development of wireless sensing technology and cyberinfrastructure frameworks for the efficient management of bridges. 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 sensing of specific damage events common to civil structures such as cracking and corrosion. Data from self-sensing materials, as well as from 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. A major achievement of the project reported in this presentation is the deployment of the project technologies on the New Carquinez Suspension Bridge and the Telegraph Road Bridge.

9063-33

Automated analysis of long-term bridge behavior using a cyber-enables wireless monitoring system

Jerome P. Lynch, Sean O’Connor, Univ. of Michigan (United States)

The holy grail for the structural health monitoring field is the creation of a scalable monitoring system architecture that abstracts many of the system details (e.g., sensors, data, etc) from the structure owner with the aim of providing “actionable” information that aids in their decision making process. While a plethora of new sensor technologies have recently emerged from academic and industrial laboratories that open unprecedented opportunities to install dense arrays of sensors on bridges, these advances have outpaced similar advances in the realm of data processing and decision support tools. This paper reports on a wireless structural health monitoring system coupled with information technologies to offer a cyber-enabled long-term health monitoring system for highway bridges. The design of the cyber-enabled wireless monitoring system is done in a top-down strategy that originates from the decision support tools needed to aid bridge owners with long-term bridge management as opposed to the traditional bottom-up approach that overly focuses on the sensors available for the creation of data. The architectural design of the monitoring system centers on a powerful database system called SenStore which is designed to combine sensor data with bridge design information (e.g., geometric details, material properties). The database exposes application programming interfaces that permit data processing tools to extract information from bridge data.

Dense networks of low-cost wireless sensors installed on a highway bridge are provided access to SenStore for autonomous storage of bridge measurement data. To convert data into information of high value to the bridge owner, automated analysis is performed on long-term bridge monitoring data. The Telegraph Road Bridge (TRB), a multi-girder steel composite bridge located in Monroe, MI, has been selected for installation of a permanent wireless sensor network designed to monitor the acceleration, strain and displacement response of the bridge to traffic and environmental loads. Data collected over a 12 month period is analyzed to extract pertinent behavioral information about the bridge of relevance to bridge management decision making.

9063-34

Multi-hazards monitoring of pin hangers

Mohammed M. Ettouney, Weidlinger Associates, Inc. (United States); Sharada Alampalli, Prospect Solutions, LLC (United States); Sreenivas Alampalli, New York State Dept. of Transportation (United States)

The use of bridge pin-hangers is prevalent in many mid-size highway bridges in the USA. These bridge components were popular due to their ease of analysis and construction. Unfortunately, their performance and inspection have not been as successful. Detecting damage in pin-hanger components visually is not easy since the corrosion or cracking in the back side of the hanger is hidden from view. Left undetected, such damage can cause sudden failure in the hangers. The catastrophic failure of the Mianus river bridge collapse in 1983 is an example of the consequences of a sudden failure of a pin-hanger component.

In general, pin-hanger components are susceptible to two silent, slow, and deadly hazards: fatigue and corrosion. (We will refer to any demand that degrade the behavior of a structural component as a 'hazard'). These two hazards are fairly different in causes, effects, and how they can be monitored. One commonality between the two hazards is that they degrade the behavior of the pin-hangers. Another commonality is that if such degradation is on the back side of the pin-hanger, visual inspection and detection of such degradation is impossible.

This work will describe a monitoring effort that aims at detecting the degrading effects of both fatigue and corrosion of pin-hangers components. As such it can be described as a multihazards monitoring system. The system combines different types of sensors (strains and accelerometers). It also relies on a hybrid algorithm that aims at detecting the combined multihazards degradation effects of fatigue and corrosion.

9063-35

Bayesian risk monitoring of bridge components

Mohammed M. Ettouney, Weidlinger Associates, Inc. (United States); Sharada Alampalli, Prospect Solutions, LLC (United States); Sreenivas Alampalli, New York State Dept. of Transportation (United States)

Employing risk-based designs and management is gaining momentum in the field of civil infrastructures. This is due to the ever increasing costs of infrastructure ownership, as well as the immense costs of unplanned interruptions of operations and / or premature failure of infrastructures. Risk principles as opposed to reliability (sometimes referred to as safety) designs integrate consequences to the design and management processes (in addition to the usual demands and capacity considerations). In addition, including uncertainties in the process might also be needed in order to provide the designer and / or manager with and even more explicit leeway in the decision making process.

Those two factors (inclusion of consequences and increased accommodation of uncertainties) require, more than ever, the accommodation of interactions between the variables in the processes. Traditionally, such interactions have been ignored, or at best treated in a marginal manner. Bayesian methods are well suited to accommodate such interactions in an efficient and well organized manner.

This work offers a description of an application of risk monitoring of bridge components using Bayesian process. The allocations of the needed conditional probabilities tables (CPT) at different nodes of the component risk are explained. The utilizations of objective and subjective as sources of those CPTs are explained. Objective sources include sensing measurements; weigh in motion, and analytical finite elements models. Subjective sources include personal judgment, past experiences, and potential inspection reports. Finally, the implementation of the process in a simple decision making tool for bridge managers is offered.

9063-36

Real-time estimation of the structural response using limited measured data

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This study introduces an efficient procedure to estimate the structural response of a suspension bridge in real-time based on a limited set of measured data. The proposed technique estimates the response of a suspension bridge structure based on a set of strain gauge measurements. The procedure uses computed flexibility matrix, computed hanger forces matrix and measured hanger forces to estimate the response of the structure. The Alfred Zampa Memorial Bridge, on Interstate 80 in California, was selected for this study. A detailed finite element model of the bridge was developed using the finite element program ADINA. The first step was to calculate the flexibility and hanger forces matrices of the bridge by applying a nominal moving force at the assumed sensor locations. Then, a truck load was applied at a desired location and hanger forces were extracted at the assumed sensor locations. In the next step, the deflection of the bridge under the truck load was estimated based on the computed flexibility matrix, computed hanger force matrix and the measured hanger forces vector. The estimated deflection response of the bridge was compared with the exact solution for several truck loading positions and different number of strain gauges. The method has been proven to have the capability to estimate any type of structural response based on the measured hanger forces, and provides an important part of an integrated Structure Health Monitoring (SHM) system for major bridges.

9063-37

Implementation of damage detection algorithms for the Alfred Zampa memorial suspension bridge

Iman Talebinejad, Hassan Sedarat, Abbas Emami-Naeini, Alex Krimotat, SC Solutions, Inc. (United States); Jerome P. Lynch, Univ. of Michigan (United States)

This study investigated a number of different damage detection algorithms for structural health monitoring of a typical suspension bridge. The Alfred Zampa Memorial Bridge, a part of the Interstate 80 in California, was selected for this study. The focus was to implement and validate simple damage detection algorithms for structural health monitoring of complex bridges. Accordingly, the numerical analysis involved development of a high fidelity finite element model of the bridge in order to simulate various structural damage scenarios. The finite element model of the bridge was calibrated based on the experimental modal properties. A number of damage scenarios were simulated by changing the stiffness of different bridge components including suspenders, main cable, bulkheads and towers. Several vibration-based

damage detection methods namely the change in the stiffness, change in the flexibility, change in the uniform load surface and change in the uniform load surface curvature were employed to locate the simulated damages. The investigation here provides the relative merits and shortcomings of these methods in long span suspension bridges.

9063-38

Vehicle-induced dynamic response of expansion joints in long span bridges

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Premature failures of modular expansion joints were found in Jiangyin Yangtze river suspension bridge and Runyang Yangtze river suspension bridge. Due to increasing traffic on both bridges, behavior of expansion joints is believed to be largely influenced by pounding impact from passing vehicles.

Dynamic response of expansion joint is complicated due to interaction between vehicle and expansion joint. In order to precisely understand behavior of expansion joint under vehicle impact loading, a new analysis scheme is proposed which comprises vehicle model and expansion joint model. Vehicle model moving at constant speed is analyzed with Newmark method in Matlab to obtain the contact force acting on the expansion joint. Expansion joint model is established in commercial Finite Element software ABAQUS with refined solid element.

Interaction between vehicle and expansion joint is realized through a global iteration procedure. Interaction force on expansion joint is obtained from dynamic analysis of vehicle model in Matlab, and then applied on the expansion joint model in ABAQUS. After the FE analysis, displacements at different contact points from expansion joint FE model are extracted and incorporated in vehicle analysis. Iteration is performed until compatibility at contact points is satisfied, which ensures the same displacement of vehicle and expansion joint at contact points. After the compatibility condition is satisfied, response of expansion joint is finally extracted to calculate dynamic amplification factor and estimate its fatigue property.

9063-39

Numerical analysis of PZT rebar active sensing system for structural health monitoring of RC structure

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Structural Health Monitoring (SHM) of reinforced concrete ?RC? structure using PZT is under wide interests and investigation. Due to the complexity of concrete microstructure and the electric-mechanical coupling effect of PZT, numerical simulation turns to be a good approach for studying and analysis of such an SHM system.

An active sensing diagnostic system using PZT-rebar for SHM of RC structure has been currently under investigation. Test results show that the system can detect the damage of the structure. To fundamentally understand the damage development algorithm and therefore to establish a robust diagnostic mechanism, an accurate Finite Element Analysis (FEA) for the system has been performed. A steel rebar with surface bonded PZT under a transient wave load is first simulated using commercial FEA software ANSYS. In the model, the rebar with PZT and epoxy layer is modeled using 2D axisymmetric type. PZT material property transformation is discussed due to the coordinate system differences between IEEE Standard and ANSYS. The simulation uses the direct coupled-field analysis module. And the selection of material properties such as Raleigh damping coefficients is discussed. The numerical model has been validated with experimental tests. The good consistency between them shows that the numerical model for PZT-rebar is reasonably accurate. Based on it, parametric study for potential signal improvement has been carried out. It is found by changing PZT layout into different configurations, output signals could be increased several times higher than the original one. Further simulation has been done for a concrete beam structure with one reinforcement bar in the middle. And rebar's debonding damage of RC beam has been simulated. By comparison, numerical outputs agree very well with experiment tests. Based on the above modeling, further research could be done for studying system's SHM algorithm of RC structure and for system development.

9063-40

Damage localization by active guided waves utilizing reflection and scattering features

Hwee Kwon Jung, HyeJin Jo, Gyuhae Park, Chonnam National Univ. (Korea, Republic of)

The use of active-sensing piezoelectric materials for structural health monitoring (SHM) applications has been extensively investigated. One of the SHM methods utilizing piezoelectric materials is guided waves, where the damage detection and location is possible by monitoring the reflection and scattering characteristics of propagated waves. . This paper presents a new signal processing technique of guided waves for damage detection and location of plate-like structures. The method is based on the previous work developed by Kundu et al. (2012) used for source identification of acoustic emission, and is extend to active-sensing guided waves in this study. The technique is based on the use of reflection and scattering features, and does not require a prior knowledge of wave speed or physical properties of a structure. Several case studies were performed on isotropic aluminum plates and on anisotropic composite plates and its capability of detecting and locating structural damage was demonstrated. This paper includes the experimental setup, procedure, and results along with several research issues to implement the technique for handling real-world applications.

9063-41

Early-age concrete strength estimation based on piezoelectric sensor using artificial neural network

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Recently, novel methods to estimate the strength of concrete have been reported based on numerous NDT methods. Especially, electro-mechanical impedance technique or ultrasonic wave methods using piezoelectric sensors are studied to estimate the strength of concrete. However, the previous research works could not provide the general information about the early-age strength important to manage the quality of concrete and/or the construction process. In order to estimate the early-age strength of concrete, the electro-mechanical impedance method and the artificial neural network(ANN) is utilized in this study. The electro-mechanical impedance varies with the mechanical properties of host structures. Because the strength development is most influential factor among the change of mechanical properties at early-age of curing, it is possible to estimate the strength of concrete by analyzing the change of E/M impedance. The strength of concrete is a complex function of several factors like mix proportion, temperature, elasticity, etc. Because of this, it is hard to mathematically derive equations about strength of concrete. The ANN can provide the solution about early-age strength of concrete without mathematical equations. To verify the proposed approach, a series of experimental studies are conducted. The impedance signals are measured using embedded piezoelectric sensors during curing process and the resonant frequency of impedance is extracted as a strength feature. The strength of concrete is calculated by regression of strength development curve obtained by destructive test. Then ANN model is established by trained using experimental

results. Finally the ANN model is verified using impedance data of other specimens.

9063-42

Phased array and nonlinear penetrating radar for concrete inspection

Dryver R. Huston, Dylan Burns, Jonathan Razinger, The Univ. of Vermont (United States)

This paper presents results of a recent study looking into the development of phased array and nonlinear ground penetrating radar (GPR) techniques. Phased array methods have been a staple technique for electronically steering atmospheric radars in ranging and locating applications. The electronic steering approach offloads the mechanical steering tasks onto microwave electronic methods. Even though electronic steering requires precise phase and amplitude control of amplified signals at microwave frequencies, many phased array systems accomplish steering agility and speed in a system that is lighter than a complete multichannel system. The demands for dense-array subsurface imaging in high speed GPR inspection vehicles raises the question as to the potential utility of phased array methods for steering a GPR system to gather the same information faster with fewer physical channels. To that end, a two-channel phased array system operating nominally over the 1-12 GHz range has been set up to verify the viability of steering to identify and locate the presence of subsurface features, such as steel reinforcing bars. Operating procedures based on a modified multichannel network analyzer operating in a harmonic single stepped frequency mode to sensing reflective targets in air and under concrete will be presented. Also presented will be estimates of the speed, agility and resolution of more general phased array GPR systems. The harmonic control of source and receiver channels also permits the direct measurement of superharmonic and intermodulation products in radar signals. The applicability of these techniques to corrosion sensing is examined.

9063-43

Advanced signal processing method for ground penetrating radar feature detection and enhancement

Tian Xia, The Univ. of Vermont (United States)

This paper focuses on new signal processing algorithms customized for an air coupled Ultra-Wideband (UWB) Ground Penetrating Radar (GPR) system targeting highway pavements and bridge deck inspections. The GPR hardware consists of a high voltage pulse generator, a high speed 8 GSps real time data acquisition unit, and a customized field-programmable gate array (FPGA) control element. In comparison to most existing GPR systems with low survey speeds, this system can survey at normal highway speed (60 mph) with a high horizontal resolution of up to 1 scan per millimeter. Due to the complexity and uncertainty of subsurface media, GPR signal enhancement is an important but tough procedure. In this GPR system, an adaptive GPR signal processing algorithm using Curvelet Transform, 2D high pass filtering and exponential scaling is proposed to remove environmental noise and clutter while the subsurface features are preserved and enhanced. First, a Curvelet Transform removes the environmental and systematic noise while maintaining the range resolution of the B-Scan. Next, an exponential scaling method compensates the signal attenuation in subsurface materials and improves the rebar signal features. Finally, mathematical models for rebar and clutter are built, and a 2D filter based on these models is applied to remove clutters and enhance rebar hyperbola in B-Scan. When compared with other GPR data processing and analysis methods that only focus on unique technique and purpose, our algorithm uses multiple signal processing techniques as a combination to present a thorough GPR signal enhancement. To test and evaluate the performance of our GPR system, rebar detection experiments in lab and subsurface feature inspection of field configurations are performed.

9063-44

Assessment of various methods for evaluating ground penetrating radar (GPR) data of concrete bridge decks

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The deterioration of concrete bridge decks is one of the most problematic issue facing Departments of Transportation (DOTs) in North America. Among various bridge elements, concrete decks usually have the highest rate of deterioration and therefore need to be inspected regularly and carefully. Since important defects in concrete bridge decks such as delamination and rebar corrosion cannot be found by visual observation, nondestructive evaluation (NDE) technologies are being studied worldwide as an alternative method for inspection. As a nondestructive evaluation (NDE) technique, the Ground Penetrating Radar (GPR) has been considered for a long time being a good technique for that purpose. Theoretically, this technology can detect common defects in concrete bridge decks such as corrosion and delamination, with high speed and precision of data collection.

Many research have been performed using GPR to assess condition of concrete bridge decks. As a result of these studies, several methods to analyze and interpret GPR data have been proposed, including: (1) Method based on reflection amplitude, (2) Method based on GPR image analysis; and (3) Method based on time-series signal correlation. Since each of these methods has its own advantages and limitations, the purpose of this paper is to report a comprehensive assessment and comparison of these analysis methods. In addition, the assessment is illustrated through a case study for real bridge decks in Canada and US.

9063-45

Denoising analysis of synthetic aperture radar images using discrete wavelet transform for the radar NDE of concrete specimens

Tzu-Yang Yu, Univ. of Massachusetts Lowell (United States)

Radar or microwave NDE has been widely used for the condition assessment of civil infrastructure systems such as buildings, bridges, and pavements. In recent years, synthetic aperture radar (SAR) imaging also has shown its potential for the subsurface damage detection of reinforced concrete structures. However, quality of SAR images is crucial to the damage detectability of subsurface defects in concrete structures, especially when distant radar inspection is performed. Denoising is necessary to remove stationary or non-stationary electromagnetic noises in SAR images in order to improve the signal-to-noise (SNR) ratio of SAR images. In this paper, discrete wavelet transform (DWT) was used in the denoising analysis of SAR images for the radar NDE of concrete specimens. Distant radar responses of several concrete specimens were collected (in an anechoic chamber and in an indoor environment) and then processed into SAR images. Daubechies wavelets were adopted in the multi-scale analysis and synthesis of SAR images. Various combinations of approximation and detail coefficients were investigated to examine the performance of denoising SAR images using DWT. It is found that, from the multi-scale analysis and synthesis of SAR images, stationary and non-stationary noises have shown different features in approximation and detail coefficients of DWT. Recommendations are made in the denoising of SAR images obtained from distant radar NDE of concrete specimens.

9063-46

Dielectric modeling of cementitious specimens using an open-ended coaxial probe in the frequency range of 0.5GHz to 4.5 GHz

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Modeling the dielectric properties of cementitious materials (e.g., cement paste, concrete) is important to the success of nondestructive evaluation (NDE) of civil engineering infrastructure using electromagnetic sensors. Information regarding material composition, aging, cracking, and chemical deterioration of cementitious materials can jointly affect the dielectric properties of the material. Reliable and accurate condition assessment of concrete structures using electromagnetic sensors cannot be achieved without the capability and knowledge of dielectric modeling of cementitious materials. Among existing dielectric measurement techniques, open-ended coaxial probe is convenient for in-situ measurement and superior for field applications than other techniques. Nonetheless, quality of coaxial probe measurements is dependent on the contact condition between the probe and the specimen. In this paper, our measurement and modeling efforts on the dielectric properties of cementitious specimens using an open-ended coaxial probe in the microwave frequency range (0.5~4.5 GHz) are reported. Fluctuation of dielectric data curves (dielectric constant and loss factor) due to the contact condition between the probe and the specimen was investigated using frequency analysis. It is found that the presence of surface pores/cavities can introduce high frequency noises into the measured dielectric data curves.

9063-47

Modeling the x-ray process and x-ray flaw size parameter for probability of detection studies

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Nondestructive evaluation (NDE) method reliability can be determined by a statistical flaw detection study called probability of detection (POD) study. In many instances the NDE flaw detectability is given as a flaw size such as crack length. The flaw is either a crack or behaving like a crack in terms of affecting the structural integrity of the material. An alternate approach is to use a more complex flaw size parameter. The X-ray flaw size parameter, given here, takes into account many setup and geometric factors. The flaw size parameter relates to X-ray image contrast and is intended to have a monotonic correlation with the POD. Some factors such as set-up parameters including X-ray energy, exposure, detector sensitivity, and material type that are not accounted for in the flaw size parameter may be accounted for in the technique calibration and controlled to meet certain quality requirements. The proposed flaw size parameter and the computer application described here give an alternate approach to conduct the POD studies. Results of the POD study can be applied to reliably detect small flaws through better assessment of effect of interaction between various geometric parameters on the flaw detectability. Moreover, a contrast simulation algorithm for a simple part-source-detector geometry using calibration data is also provided for the POD estimation.

9063-48

Distributed point source method for the modeling of a three-dimensional eddy current NDE problem

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The basic principle of EC NDE techniques is based on the use of i) a contactless electromagnetic inducer able to induce ECs within the part under evaluation, and ii) a measurement set-up able to measure, at the surface of the part, the magnetic field resulting from the interactions between the ECs and the part. This method is widely used since it is easy to use and sensitive to local changes of the part features (e.g. cracks, holes, inclusions…). However, because of the diffusive nature of the propagation of the magnetic field within the part, as well as the presence of the air / part interface, it is generally complicated to directly correlate the variations of the measured field with the changes of the part features responsible for these variations. To do so, it is necessary to use an accurate and computationally efficient modeling tool able to foresee and evaluate these interactions. Among the modeling methods, the distributed point source method (DPSM) is a good candidate, since it is accurate, efficient as well as versatile. Indeed, the DPSM is a mesh-free semi-analytical method, particularly well fitted to the three-dimensional modeling of the interactions of fields with media of any geometry, in the case of electromagnetic, electrostatic or ultrasonic problems. In this paper, the DPSM is implemented to model the interactions induced by a uniformly oriented EC imaging system with aluminum assemblies featuring notch-type defects. The modeling results obtained for various defects features are presented, discussed and compared to measured data.

9063-49a

ANDERS: merging of automated and minimally invasive technologies for concrete bridge deck evaluation and rehabilitation *(Keynote Presentation)*

Nenad Gucunski, Rutgers, The State Univ. of New Jersey (United States)

The Automated Nondestructive Evaluation and Rehabilitation System (ANDERS) aims to provide a uniquely comprehensive tool that will transform the manner in which bridge decks are assessed and rehabilitated. It is going to be achieved through: 1) much higher evaluation detail and comprehensiveness of detection at an early stage deterioration, 2) comprehensive condition and structural assessment at all stages of deterioration, and 3) integrated assessment and rehabilitation that will be minimally invasive, rapid and cost effective. ANDERS is composed of three physical systems that merge novel NDE technologies together with novel intervention approaches to arrest the deterioration processes. These technologies are incorporated within a series of human-operated and robotic vehicles to allow rapid, comprehensive application across large populations of bridges. To perform assessments, ANDERS is equipped with two complimentary nondestructive approaches. The first, Multi-Modal Nondestructive Evaluation (MM-NDE) System aims to identify and characterize localized deterioration with a high degree of resolution. The second, global structural assessment system named STAR aims to capture global structural characteristics and identify any appreciable effects of deterioration on a bridge structure. Output from these two approaches will be merged through a novel Automated Structural Identification (Auto St-Id) approach that constructs, calibrates, and utilizes simulation models to assess the overall structural vulnerability and capacity. These two systems comprise the assessment suite of ANDERS and directly inform the Nondestructive Rehabilitation (NDR) System. The NDR System leverages robotics for the precision and rapid delivery of novel

materials capable of halting the early-stage deterioration identified. The paper covers the details of the three ANDERS components developed through the support from National Institute of Standards and Technology-Technology Innovation Program (NIST-TIP). Specifically, the paper will provide a description of the components, their principle of operation and applications, and describe how the components work together.

9063-50a

Recent development on remote sensing and wireless communication with distributed smart rocks in bridge scour monitoring

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In the U.S., scour is the No. 1 cause for over 1500 bridge collapses during the past 40 years. The maximum scour depth is the most critical parameter in bridge design and maintenance. Due to scour and refilling of river-bed deposits, existing technologies face a challenge in measuring the maximum scour depth during a strong flood event. In this study, an overview on a recent two-year study of both passive and active smart rocks methodologies is given. Passive smart rocks are rocks with embedded permanent magnets whose intensity was measured at distance using a magnetometer. By triangulation, a passive smart rock can be located from the magnetic field intensities measured with a magnetometer from at least three stations as the embedded magnets are oriented in different angles. Active smart rocks are rocks with embedded electronics so that the rocks can be waken, take pertinent data, and transmit useful information to a receiving station. Each active smart rock is equipped with a 3-axis accelerometer, a 3-axis magnetometer, a gyroscope, a pressure sensor as needed, an ID, a timer, a battery level indicator, and an antenna with magneto-inductive wireless communication. The active smart rock can communicate with a base station or other smart rocks to form a local wireless network. It can be located with received signal strength indications from the base station and the other smart rocks. Both laboratory and field tests were conducted to calibrate, characterize, and validate various smart rocks.

9063-51a

Comparative testing of nondestructive evaluation techniques for concrete structures

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A multitude of concrete-based structures are typically part of a light water reactor (LWR) plant to provide foundation, support, shielding, and containment functions. Concrete has been used in the construction of nuclear power plants (NPPs) because of three primary properties, its inexpensiveness, its structural strength, and its ability to shield radiation. Examples of concrete structures important to the safety of LWR plants include containment building, spent fuel pool, and cooling towers. Comparative testing of the various NDE concrete measurement techniques requires concrete samples with known material properties, voids, internal microstructure flaws, and reinforcement locations. These samples can be artificially created under laboratory conditions where the various properties can be controlled. Other than NPPs, there are not many applications where critical concrete structures are as thick and reinforced. Therefore, there are not many industries other than the nuclear power plant or power plant industry that are interested in performing NDE on thick and reinforced concrete structures. This leads to the lack of readily available samples of thick and heavily reinforced concrete for performing NDE evaluations, research, and training. The industry that typically performs the most NDE on concrete structures is the bridge and roadway industry. While bridge and roadway structures are thinner and less reinforced, they have a good base of NDE research to support their field NDE programs to detect, identify, and repair concrete failures. This paper will summarize the initial comparative testing of two concrete samples with an emphasis on how these techniques could perform on NPP concrete structures.

9063-52a

A modular backend computing system for continuous civil structural health monitoring

Ting-Chou Chien, Pai H. Chu, Chengjia Huo, Univ. of California, Irvine (United States)

This paper describes a computing backend for a waterpipe monitoring system. Today, most such systems are divided into event-triggered and continuous monitoring, but they all lack systematic handling of data. Many systems simply store data in files with specific naming conventions and ad hoc formats, making them difficult to retrieve, maintain, disseminate, and analyze.

To address these problems, our backend supports data management and dissemination. Unlike previous systems that store data in files or conventional databases before analysis, our modular architecture not only saves data in efficiently searchable ways by indexing as a baseline dataset but also detected events in discrete time manner and other processed data. To facilitate analysis, we design a plug-in structure to allow processing modules to perform inline processing and shorten detection time. For data dissemination, our architecture can compose multiple visualizations including geographical maps to create powerful tools to yield new insight into massive datasets. The backend system enables Internet web service for visualization, data management, and remote sensor control for better integration. Our system is applicable to not only water pipelines but also bridges and civil structures in general.

Our proposed backend system has been implemented and validated through field deployment. One such system has been running for over 1.5 years and has collected millions of records to date. A Google Map integrated visualization service has been developed to demonstrate lively collected records in real-time. This is expected to be more helpful for better understanding of civil structures' behavior in the long term.

9063-53a

Wireless monitoring of the height of condensed water in steam pipes

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A wireless health monitoring system has been developed for determining the height of water condensation in the steam pipes and the data acquisition is done remotely using a wireless network system. The developed system is designed to operate in the harsh environment encountered at manholes and the pipe high temperature of over 200oC. The test method is an ultrasonic pulse-echo and the hardware includes a pulser, receiver and wireless modem for communication. Data acquisition and signal processing software were developed to determine the water height using adaptive signal processing and data communication that can be controlled while the hardware is installed in a manhole. A statistical decision-making tool is being developed based on the field test data to identify the changes in the condensed water under high noise conditions and other environmental factors. The details of the wireless sensing system, its functions, and design considerations will be described and discussed in this paper.

9063-54a

Remote monitoring and nondestructive evaluation of wind turbine towers

Chih-Hung Chiang, Chih-Peng Yu, Keng-Tsang Hsu, Chia-Chi Cheng, Ying-Tzu Ke, Chaoyang Univ. of Technology (Taiwan)

Wind turbine towers and industrial chimneys are in need of condition monitoring so as to lower the cost of unexpected maintenance. Technicians who perform visual inspection are at high risk because of the height of towers. Current study aims to apply remote inspection and monitoring techniques to tower structures so as to reduce the risk of inspection. Remote microwave interferometry and structural dynamic analyses are explored in this respect. Periodic monitoring of a wind turbine tower using a step-frequency-continuous-wave microwave interferometry system has been conducted over 18 months. The height of the turbine nacelle is 65m from the ground. Welding at each sections of the steel tower provide good reflection signals for the microwave interferometry system on the ground. The measured vibration frequency is 0.44Hz for the fundamental mode of the tower. Different vibration modes of the tower are characterized at different rotation speed of the turbine. The turbine-tower interaction will be further investigated using spectral finite element methods. The dynamic stiffness change at some location can be analyzed in the frequency domain that in turn can be verified using remote microwave interfermoetry. Expected outcome will include the remote monitoring procedures and nondestructive evaluation techniques for local utility tower structures.

9063-55a

Design, fabrication, and validation of passive wireless resonant sensors for NDT/SHM

Michele Meo, Univ. of Bath (United Kingdom)

The objective of this research work was to create and validate a low cost smart-sensor for aerospace structural health monitoring (SHM) that could be embedded in complex geometries.

The sensor utilizes a passive wireless resonant telemetry scheme based on an inductor capacitor (LC). The use of a passive system eliminates the need for onboard power and exposed interconnects, increasing the life of the device and the reliability due to the continuous operation even in case of a damaged sensor.

The sensor design, the signal processing and the experimental setup that validate the remote interrogation of the antenna sensor are presented. Two different designs were investigated, one for conductive surface (aluminium) and one for nonconductive surface (fiberglass-composite). Tests to determine the maximum interrogation range were undertaken and compared with the analytical result.

The smart-sensor was able to determine the presence of delaminations or barely visible defects present inside the samples. The capability of the sensor was also investigated in presence of surface cracks that caused damage to the proposed sensor. Test results demonstrated that in this case the sensor was able to provide its function with a different resonant frequency.

9063-56b

NDE of ceramic matrix composites subjected to impact damage

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With the upcoming implementation of ceramic matrix composites within turbine engines, an in-depth understanding of foreign object damage is required. This includes developing a data base of post impact properties as well as the associated nondestructive evaluation (NDE) techniques that are capable of recognizing and quantifying the rather complex impact related damage. To address this requirement, silicon carbide fiber/silicon carbide matrix (SiC/SiC) coupons were impacted using high speed projectiles with velocities up to 360 m/s. For this study, the details and results of two NDE techniques, an acousto-ultrasonics (AU) scan system and pulsed thermography, are presented. The damage states were assessed using the NDE techniques with the NDE results also being compared to x-ray computed tomography data and optical observations of intact and sectioned coupons. Lastly, select coupons were used for post impact uniaxial tensile tests in an attempt to correlate residual strengths to the AU and pulsed thermography data.

9063-57b

Non-destructive evaluation of delamination growth in glass fiber composites using optical coherence tomography

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Composite materials have been widely used in engineering fields due to their advantages including light weight, high stiffness and strength. However, the mechanical performance of composite materials may degrade severely in the presence of damage. Defects such as delamination could bring catastrophic failure of the materials and hence significantly shorten the lifetime of the structures. To understand the behavior of delamination as well as its propagation, NDT techniques with high resolution are needed. Optical coherence tomography (OCT) is a contactless and non-destructive technique for microstructural diagnosis of turbid media. In the past 20 years it has been continuously developed and nearly exclusively applied for biomedical imaging of tissues while OCT-based methods for non-biomedical investigation tasks, e.g. within the field of non-destructive testing (NDT) for material inspection, are much less reported. Therefore, the aim of this study is to demonstrate and evaluate the capability of OCT as a novel NDT tool for material characterization. Based on low coherence interferometry, a robust fiber-optical OCT system has been built. The system was used to monitor the crack growth of a delamination between the middle layers of a glass fiber composite under a static loading. A tensile test setup was designed as well to couple with the OCT instrument. To process the acquired data, an optimized signal processing algorithm was developed. Finally by the 3D reconstruction of the crack profile, the crack structure inside the composite material at different stages during the propagation of the delamination was demonstrated for the first time to the best of our knowledge.

9063-58b

Detecting subsurface damage in composites using embedded multilayered thin film sensor

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Fiber-reinforced polymers are used as main structural components in many aerospace, civil, automobile, and wind turbine structures, primarily due to their excellent mechanical properties and low mass densities. Despite these advantages, composites are susceptible to different damage modes, and many of which are not visible to the naked eye. This makes the current adopted method of visual inspection challenging. In this study, a carbon nanotube-based thin film sensor was employed for detecting spatially distributed damage in composite structures. Previous studies demonstrated that film resistivity/conductivity was linearly related to applied strains, thus validating its strain sensitivity or piezoresistivity.

Furthermore, when an electrical impedance tomography (EIT) algorithm was employed for obtaining the spatial conductivity distribution of these thin films, it was shown that this technique could achieve spatial damage detection. Not only could the severity of damage be quantified, but the location of damage could also be identified. This study continued this investigation by embedding multiple layers of thin film sensors within glass fiber-reinforced polymer (GFRP) composite panels. Three-point bending and impact tests were performed to inflict damage to the GFRP specimens. The spatial conductivity maps of the embedded films were obtained to track the formation and propagation of damage through the thickness of the composite structure.

9063-59b

Guided wave propagation study on laminated composites by frequency-wavenumber technique

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Ultrasonic guided waves have proved useful for structural health monitoring (SHM) and nondestructive evaluation (NDE) due to their ability to propagate long distances with less energy loss compared to bulk waves and due to their sensitivity to small defects in the structure. However, there remain many challenging tasks for guided wave based SHM due to the complexity involved with propagating guided waves, especially in the case of composite materials. The multimodal nature of guided waves and anisotropy in composite materials significantly complicate the wave analysis.

This paper studies wave propagation in laminated composites and wave interaction with delamination damages using frequency-wavenumber analysis. Both elastodynatic finite integration technique (EFIT) modeling and scanning laser vibrometer sensing are used to acquire the wavefield data in the subject laminated carbon fiber reinforced polymer (CFRP) composites. Teflon inserts are used to simulate delamination damages. The acquired wavefield data are converted to frequency-wavenumber domain by multi-dimensional Fourier analysis. The wave representation in frequency-wavenumber domain not only shows discernible wave modes that propagate in different directions providing an easy means to determine mode composition, but also allows for the visualization of mode conversion. Wave interaction with delamination through frequency-wavenumber technique reveals trapped energy within the delaminated area. The possibility of mode extraction is also explored and its potential for damage detection in laminated composites is discussed in the end.

9063-60b

Patch antenna based temperature sensor

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Based on the transmission line model, the resonant frequency of a patch antenna is related to its physical dimensions and to the dielectric constant of the substrate material2. Temperature changes imposed on a patch antenna will cause the resonant frequency to shift due to changes in patch dimension and dielectric constant of the substrate material. The response of the sensor to the changes in temperature can be calculated using the coefficient of thermal expansion (CTE) and thermal coefficient of dielectric constant (TCDk) of the substrate. When the sensor is bonded to a metal with a different CTE than that of the substrate, a thermal strain is induced on the sensor, which also contributes to the shift in resonant frequency. By careful selection of the substrate material, frequency shifts on the order of hundreds of kilohertz per degree Celsius can be experienced. Experiments were conducted to investigate the thermal performance of patch antenna sensors bonded to aluminum, steel, and copper blocks with a high temperature epoxy. Thermocouples were placed on the metal blocks and connected to National Instruments data acquisition equipment to take the temperature readings. A LabVIEW code was written to control and acquire data from the network analyzer and NI equipment. S11 curves were collected at several temperatures during heating and cooling cycles. MATLAB codes were developed to perform the data reduction. The shift in resonant frequency due to temperature change was calculated and compared to analytical predictions.

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9063-61b

Modeling stability of flap-enabled HAWT blades using spinning finite elements

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Horizontal-axis wind turbines (HAWTs) are growing in size and popularity for the generation of renewable energy to meet the world’s ever-increasing demand. Long-term safety and stability are major concerns related to the construction and use-phase of these structures. Braking and active pitch control are important tools to help maintain safe and stable operation, however variable cross-section control represents another possible tool as well. To properly evaluate the usefulness of this approach, modeling tools capable of representing the dynamic behavior of blades with conformable cross sections are necessary. In this study, a modeling method for representing turbine blades as a series of interconnected spinning finite elements (SPEs) as presented where the aerodynamic properties of individual elements may be altered to represent changes in the cross section due to conformability (e.g., use of a mechanical flap or a “smart” conformable surface). Such a model is expected to be highly valuable in design of control rules for HAWT blades with conformable elements. Sensitivity and stability of the modeling approach are explored.

9063-62b

Delamination detection in composite beams using system identification

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The current work focuses on application of ERA based System Identification to identify, locate and assess the size of delaminations in laminated composite beams. Unlike the use of frequency measurements, system identification has the potential to readily pinpoint the location and the extent of damage, in addition to alerting to its occurrence. Most importantly, while most techniques require measurements from the undamaged structure, System Identification can indicate and assess local damage by comparison with the rest of the structure; so measurements on the structure in its pristine condition is unnecessary. In the present study, we demonstrate the application of System Identification using ERA to detect delaminations in composite laminates and assess their location and severity.

The numerical simulation was performed with ANSYS 13.0, to model Carbon Fibre Reinforced Plastic (CFRP) beams with simulated delaminations and generate transient impulse response signals. The impulse response and the input signals are fed into the ERA algorithm to estimate the system dynamic properties, namely the stiffness and damping coefficients of all elements in the structure. Variations in the dynamic properties readily identify the presence, location and severity

of the damage. The numerical simulation of 8 ply quasi-isotropic CFRP laminated beams demonstrate that delaminations as small as one percent of the beam length in size can be identified and assessed using the present method. Experimental simulations indicate that noise in the measured impulse signals need to be eliminated for successful practical implementation of the technique.

9063-63b

Use of nondestructive inspection and fiber optic sensing for damage characterization in carbon fiber fuselage structure

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To investigate a variety of nondestructive inspection technologies and assess impact damage characteristics in carbon fiber aircraft structure, the FAA Airworthiness Assurance Center, operated by Sandia National Labs, fabricated and impact tested two full-scale composite fuselage sections. The panels are representative of structure seen on advanced composite transport category aircraft and measured approximately 56”x76”. The structural components consisted of a 16 ply skin, co-cured, hat-section stringers, fastened shear ties and frames. The material used to fabricate the panels was T800 unidirectional pre-preg (BMS 8-276) and was processed in an autoclave. Simulated hail impact testing was conducted on the panels using a high velocity gas gun with 2.4” diameter ice balls in collaboration with the University of California San Diego (UCSD). Damage was mapped onto the surface of the panels using conventional, hand deployed ultrasonic inspection techniques, as well as more advanced ultrasonic, laser ultrasonic and resonance scanning techniques. In addition to the simulated hail impact testing performed on the panels, 2” diameter steel tip impacts were used to produce representative impact damage which can occur during heavy ground maintenance operations. The extent of impact damage ranges from less than 1 in2 to 55 in2 of interply delamination in the 16 ply skin. Substructure damage on the panels includes shear tie cracking and stringer flange disbonding. It was demonstrated that the fiber optic distributed strain sensing system could detect impact damage when bonded to the backside of the fuselage.

9063-64a

Quantifying uncertainties in structural dynamic characteristics using hybrid modeling through Bayesian inference

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Quantifying uncertainties in the model of a structure and in its dynamic characteristics plays a critically important role in structural damage detection and robust design. Currently, the deviation between the model and an actual structure is generally identified through a so-called model updating process, in which a set of experimental measurement of structural dynamic response is used in combination with the model prediction to facilitate an inverse analysis that is usually deterministic. In reality, however, structural properties, such as mass and stiffness, are inevitably subject to variation/uncertainties. As such, the identification of property variations in a probabilistic manner can truly reveal the underlying physical characteristics of the structure involved. In this research, we adopt a Bayesian inference-based Gaussian process regression to identify the distribution of structural parameters. A few selected samples of incompletely measured modes extracted from experiment are considered as the training data for this inference network. The inference will yield probabilistic distributions of both the model parameters and the dynamic responses. The effectiveness of this proposed method is demonstrated by a laboratory case study.

9063-65a

A comparison of several global optimization algorithms with sequential niche technique for structural model updating

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Much effort is devoted nowadays to derive accurate finite element (FE) models to be used for structural health monitoring, damage detection and assessment. However, formation of a FE model representative of the original structure is a difficult task. Model updating is a branch of optimization which calibrates the FE model by comparing the modal properties of the actual structure with these of the FE predictions. As the number of experimental measurements is usually much smaller than the number of uncertain parameters, and, consequently, not all uncertain parameters are selected for model updating, different local minima may exist in the solution space. Experimental noise further exacerbates the problem. The attainment of a global solution in a multi dimensional search space is a challenging problem. Global optimization algorithms (GOAs) have received interest in the previous decade to solve this problem, but no GOA can ensure the detection of the global minimum either. To counter this problem, a combination of GOA with sequential niche technique (SNT) has been proposed in this research which systematically searches the whole solution space. A dynamically tested full scale pedestrian bridge is taken as a case study. Three different GOAs, namely Particle Swarm Optimization (PSO), Genetic Algorithm (GA) and Simulated Annealing (SA), have been investigated in combination with SNT. The results of all the GOA are compared in terms of efficiency of detection of minima. The systematic search enabled to find different solutions in the search space thus increasing the confidence of finding the global minimum.

9063-66a

Substructure model updating through iterative minimization of modal dynamic residual

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Structural behavior predicted by finite element models built according to the design drawings is usually different from the behavior of an actual structure in the field, owing to the high complexity of civil structures. Therefore, for higher accuracy, it is essential to correct finite element models based on experimental measurement. Numerous model updating algorithms have been developed in the past few decades. However, when applied to the high-resolution model of large structure, most existing algorithms suffer computational challenges and convergence problem. The difficulties come from the fact that most existing algorithms operate on the entire structural model with very large amount of degrees of freedom. To address the difficulties, this research investigates a substructure model updating approach. Craig-Bampton theory is adopted to condense the entire structural model into a substructure (currently being analyzed) and the residual structure. Finite element model of the substructure remains at high resolution, while dynamic behavior of the residual structure is approximated using only a limited number of dominant mode shapes. As a result, experimental measurement can focus on the substructure only. To update the condensed structural model, the physical parameters of the substructure and modal parameters of the residues structure are the chosen as optimization variables, and minimization of the modal dynamic residual is chosen as the optimization objective. An iterative linearization procedure is adopted for efficiently solving the optimization problem. This substructure

model updating procedure, which minimizes modal dynamic residual, is validated by numerical simulation with a plane truss model and a portal frame model. The performance is compared with a conventional updating procedure that minimizes modal property differences.

9063-67b

The evaluation of moisture damage for CFRC pipes in conjunction with acoustic emission

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The objective of this study was to evaluate the in-situ serviceability of Cellulose Fiber Reinforced Concrete (CFRC) pipes using Acoustic Emission (AE). Three-edge-bearing test was conducted on CFRC pipes in the laboratory in accordance with ASTM C497-05. Pipes were saturated in water for various periods of time to simulate the practical field situations of CFRC pipes with different service life exposed to moisture effects. AE sensors, strain gages, and LVDT were installed on pipes detect the damage phases during loading. Both monotonic and cyclic loading modes were conducted on the CFRC pipes. Results showed that the CFRC pipes generally exhibited the nonlinear load-displacement behavior before failure, yet the level of ductility reduced with longer exposure to moisture condition. AE data were evaluated through several feature signals, including signal strength, historic index, amplitude versus duration, intensity analysis, and calm ratio analysis. Results showed that AE can detect the onset of damage and the ultimate failure of CFRC pipes. Additionally, the analysis on CFRC pipes subjected to various moisture effects showed different features of AE results. The calm ratio results showed that the calm ratio versus load ratio relations can distinguish different periods of exposure to moisture and levels of ductility, which make it feasible to monitor the health of CFRC pipes as per moisture effects.

9063-68b

Evaluation of micro-damage accumulation in holed plain-woven CFRP composite under fatigue loading

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Plain woven carbon fiber reinforced polymer (CFRP) is widely used nowadays, especially in automotive and aerospace industries. Damage due to fatigue decreases the mechanical properties of composites, and consequences can be tremendous. For example, wide spread damage due to fatigue is critical issue in aircraft design. So detection in the early stage and prediction of micro-damage are of great interest.

Fluorescent method is used in our experiments to detect micro-damage. First, different amounts of micro-damage are obtained by conducting fatigue tests to specimens with different hole-hole spacing. Followed by immersing these two-hole CFRP specimens with different amounts of micro-damage in fluorescent dye (p-methyl-red) solution for a certain time. Different amounts of dyes diffuse into sites with different amounts of micro-damage. Also time is needed for dyes to diffuse, therefore more dyes are near the surface. Thus different fluorescent intensity gradients can be obtained. The relationship between amounts of micro-damage and fluorescent intensity can be revealed.

After that, using a finite element model double-holed CFRP specimen, the strain distribution that causes fatigue damage in CFRP specimen is calculated. The results from modeling and experiments are compared. Relating the fluorescence intensity change to the degree of strain concentration, the method to evaluate the degree of microdamage at the very initial stage of fatigue based on fluorescence intensity change is discussed.

9063-69b

Nondestructive inspection of composite plates using A0 mode of Lamb waves

Rahim Gorgin, Zhanjun Wu, Dongyue Gao, Yishou Wang, Dalian Univ. of Technology (China)

In this study, a Lamb wave based nondestructive technique is developed to detect and characterize hidden defects of composite plates using a mobile hand-made PZT transducer set. Lamb waves offer an attractive complementary tool for improving inspection techniques due to their large propagation range and sensitivity to defects in their propagation path. To generate and collect Lamb wave signals, a mobile hand-made transducer set contains a PZT sensor collocated an actuator is developed. A kind of grease lubricant was used between the bottom surface of PZT actuator and the surface of the specimens to generate comparatively pure A0 mode which facilitate the identification of scattered wave features. A baseline-free imaging technique is presented in order to highlight the most probable location of damage in inspection area without relying on any baseline data. Current signal at different locations of structure is collected. Subsequently, the energy of damage scattered signal is obtained and used as a damage-sensitive feature to construct the diagnostic image. Conventional NDT methods, such as ultrasonic C-scans and X-rays, or other damage-imaging techniques can then be used once damage is found to identify the damage in detail. The approach was validated by predicting representative single and multi-damage in glass/epoxy composite plates. In order to simulate delamination damage, an added mass of an aluminum cylinder was bonded on the top surface of composite plate. The obtained experimental results at different central frequencies demonstrated the potential of the developed algorithm in defining the most probable location of damages in composite plates.

9063-70

Coupling mechanism of granular medium and slender beams

Luyao Cai, Piervincenzo Rizzo, Kaiyuan Li, Univ. of Pittsburgh (United States); Leith Al-Nazer, Federal Railroad Administration (United States)

We present a methodology to assess slender beams by means of highly nonlinear solitary waves. This can be accomplished by understanding the coupling mechanism between highly nonlinear solitary waves propagating along a granular system and slender beams in contact with the granular medium. Nonlinear solitary waves are compact non-dispersive waves that can form and travel in nonlinear systems such as one-dimensional chains of particles. In the study presented in this paper, they wave are generated by the mechanical impact of a striker and are detected by means of sensor beads located along the chain. We investigated numerically and experimentally the effect on the solitary waves of slender beams of different modulus, length, boundary condition, and axial stress. We found that the geometric and mechanical properties of the beam or thermal stress applied to the beam alter certain features of the solitary waves. In the future, these findings may be used to develop a novel sensing system for the NDE of beams.

9063-71

Application of a general purpose finite element code investigations of multiple physics in the field of rotordynamics

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Classical rotordynamics software packages are very accurate in calculating the structural dynamics of the rotor system. However, they are very limited in terms of accounting for other physical interactions which may influence the rotor's dynamic characteristics. Such effects can include thermal loads, electromagnetic loads, fluid interaction, etc. The general purpose software Comsol Multiphysics is applied to perform rotordynamic calculation with additional physical effects included.

9063-72

Non-contact flaw imaging for pipeline structures of nuclear power plants using pulsed laser system

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Recently, the longitudinal, shear and surface waves have been used to an ultrasonic wave exploration method to identify internal defects for pipeline structures of nuclear power plants. Accordingly, a noncontact NDT method is implemented to detect the damage of pipeline structures and to identify the location of the damage in this study. To achieve this goal, an ND: YAG pulsed laser system is used to generate guided waves and a galvanometer-based laser scanner scans a specific area to find damage location. Then, an air-coupled transducer is installed for fully non-contact inspection. The measured time and spatial responses are transformed to data in frequency and wavenumber domain through 3-dimensional Fourier transform. If propagating waves encounter a discontinuity point such as a crack, the waves are reflected and refracted. Therefore, damage-sensitive features can be obtained by extracting standing waves at the damage using wavenumber filter which eliminates strong incident waves. A flaw imaging technique of a pipeline structure is conducted using the damage-sensitive features. Notches and thickness reduction at a pipeline structures were investigated to verify the effectiveness and the robustness of the proposed NDT approach. Additionally, a series of experiments were repeated under heating condition to consider the environment of nuclear power plants.

9063-73

Particle filter-based hybrid prognosis for fatigue life prediction in metallic structures

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It is essential to develop a reliable prognostics framework, which can accurately predict the fatigue life of critical metallic components that are subjected to a variety of in-service loading conditions. A hybrid prognostic model combined with a particle filtering approach, which can accurately predict the crack growth regime in aluminum components, is developed. The hybrid prognostic model combines a physics based approach with a data driven approach to predict the crack growth and the residual useful life. In this approach, particle filtering is used to optimally combine the measured crack location from a Lamb wave based localization algorithm with the predicted crack location from the hybrid prognostic model to probabilistically estimate a future crack location. The localization algorithm accounts for uncertainty in time-of-flight measurements using probabilistic data association. The mean and variance of a future crack location predicted by the prognosis model is entered into the data association algorithm to be used as a priori knowledge to increase the accuracy of the crack location estimation. The hybrid prognostic model is first validated for different types of loading conditions such as constant amplitude loading, random loading and overloads. Then, the crack location estimates for a growing fatigue crack in an aluminum lug joint with and without particle filtering are presented to demonstrate the benefit of using a particle filter to combine prognostic and localization algorithms.

9063-74

A multiscale XFEM-based algorithm for detection of multiple flaws in structures

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This paper investigates a novel multiscale eXtended Finite Element Method (XFEM)-based algorithm for detection of multiple flaws and/or damage regions in structures. The proposed algorithm can be applied to quantify any "generalized" flaw with arbitrary shape and size (e.g., cracks, voids, or their combination) whose number is unknown beforehand. The basic concept is that we present a two-scale optimization framework consisting of hierarchical optimizers to solve the inverse problem. The candidate flaws keep changing by adjusting their parameters using the optimizers, in which an XFEM model with both circular and elliptical enrichments is used to solve the forward problem. The proposed hierarchical optimizers include both heuristic and gradient-based algorithms, such as the continuous and discrete artificial bee colony (ABC) algorithms and the Broyden-Fletcher-Goldfarb-Shanno (BFGS) method. In details, the first step employs a discrete ABC optimization for a coarse scale search where the optimizer is limited to specific locations and shapes of a flaw, thus converting a continuous optimization problem into a discrete optimization with a small number of choices. Then the search space reduction is conducted, in the second step, by defining local subdomains of the damage areas based on the currently identified flaw parameters. Finally, the BFGS method or the continuous ABC algorithm is implemented, in the third step, for a fine scale search taking the preliminary result in the first step as an initial guess within the subdomains. Several benchmark numerical examples are illustrated, which show that the proposed algorithm is robust, efficient and yields quite accurate flaw detection results.

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9064-1a

Nonlinear damage detection in composite structures using bispectral analysis

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Literature offers a quantitative number of diagnostic methods that can continuously provide detailed information of the material defects and damages in aerospace and civil engineering applications. Indeed, low velocity impact damages can considerably degrade the integrity of structural components and, if not detected, they can result in catastrophic failure conditions.

This paper presents a nonlinear Structural Health Monitoring (SHM) method, based on ultrasonic guided waves (GW), for the detection of the nonlinear signature in a damaged composite structure. The proposed technique, based on a bispectral analysis of two ultrasonic input waveforms, allows for the evaluation of the nonlinear response due to the presence of cracks and delaminations. Indeed, such a methodology was used to characterize the nonlinear behaviour of the structure, by exploiting the frequency mixing of the original waveforms acquired from a sparse array of sensors. The robustness of bispectral analysis was experimentally demonstrated on a damaged carbon fibre reinforce plastic (CFRP) composite panel, and the nonlinear source was retrieved with a high level of accuracy. Unlike other ultrasonic method for damage detection, this methodology does not require any baseline with the undamaged structure for the evaluation of the nonlinear source, nor a priori knowledge of the mechanical properties of the specimen. Moreover, bispectral analysis can be considered as a nonlinear elastic wave spectroscopy (NEWS) technique for materials showing either classical or non-classical nonlinear behaviour.

9064-2a

The need for a refined definition of the established elasto-acoustic coupling coefficient and the influence of pseudo-anharmonic effects

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Under reversible deformation caused by external loads anharmonic effects and stress stiffening are the two major causes for the observed variation of the transport properties of ultrasonic waves in materials used for load carrying structures. As demonstrated, these effects depend on the actual mode and for Lamb waves within one branch of a mode even on frequency. Therefore a single coefficient can not identify the respective material properties. Furthermore the historical definition covers the variation of the velocity of ultrasonic waves whereas in practical application the time-of-flight is monitored and that under varying transport length caused by the response to the applied external stress. Examples for the complex dependences are presented and suitable definitions for the description of the observed coupling are discussed. The effect, that a perfectly harmonic material would under stress exhibit a variation of the velocity of sound is attributed to pseudo-anharmonic effects, present since the path is not suitably attached to the elongating sample – as are fortunately the transducers usually used for monitoring.

9064-3a

Characterization of limestone rock using a non-collinear ultrasonic wave mixing approach

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Limestone makes up approximately 10% of the total volume of all sedimentary rocks. Limestone is used in many applications such as building materials in architecture applications, e.g. dimension stone cladding, and as aggregates in pavements such as asphalt concrete pavements.

In linear elastic wave propagation, superposition holds: two or more waves can cross paths and their resultant (in the region which they cross paths) is the addition (i.e., superposition) of those waves. However, when the media is nonlinear superposition does not hold. Because of the presence of higher-order terms in the nonlinear equations of motion, when two waves intersect, a third wave, i.e., a scattered wave may arise. However, in order for a strong scattered wave to occur, resonance and polarization conditions must be met.

A scattered shear wave was detected in dolomitic limestone rock using a non-collinear wave mixing approach, where two dilatational waves were forced to intersect at a prescribed angle. Criteria were used to assure that the detected shear wave originated via wave interaction in the limestone and not from nonlinearities in the testing equipment. These criteria included frequency and propagating direction of the resultant shear wave, and the time-of-flight separation between the two primary dilatational waves and the resulting scattered shear wave. The predicted arrival time for the scattered shear wave, i.e., difference signal, was found to match closely (≈1% difference) with the theoretical arrival time.

9064-4a

Fatigue damage characterization using time-domain features extracted from nonlinear Lamb wave signals

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Nonlinear Lamb waves have proven sensitivity to microscopic fatigue damage that can hardly be identified using traditional detection techniques. A characterization method for fatigue damage is established using nonlinear Lamb waves in conjunction with the use of a piezoelectric sensor network. An analytical model is first developed to interpret the methodology using time-domain features, extracted from nonlinear Lamb wave signals, for damage localization. This process involves a time-frequency analysis that enables the damage-induced nonlinear signal features, which is either undiscernible in original time history or uninformative in frequency spectrum, to be revealed. Subsequently, a finite element modeling technique is developed, accounting for various sources of nonlinearities in the medium bearing fatigue damage. A piezoelectric sensor network is configured to actively generate probing Lamb waves and acquire damage-induced nonlinear waves. Aided with an acoustic nonlinearity parameter developed for quantifying the nonlinearity of Lamb waves, a probability-based diagnostic imaging algorithm is further proposed, able to present the characterization results in intuitive diagnostic images. The approach is experimentally verified using a fatigue-damaged aluminum plate, showing reasonably

good accuracy. Compared to the existing nonlinear ultrasonics-based inspection techniques, this proposed approach uses a permanently attached sensor network accommodating automated online health monitoring, and more significantly, it introduces a new concept of "going back from frequency to time domain" to the spectral analysis, endowing the approach with a capacity of quantitative characterization of fatigue damage with improved localization accuracy.

9064-5a

Development of a wireless nonlinear wave modulation spectroscopy (NWMS) sensor node for fatigue crack detection

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Fatigue crack is one of the primary causes for the failure of metallic structures in infrastructure. As a new research interest, nonlinear wave modulation spectroscopy (NWMS) has been used to evaluate nonlinear acoustic signature of fatigue cracks in materials and thus to get an idea about the degree of material nonlinearity. In this study, a wireless active sensing node for fatigue crack detection is developed based on NWMS. Using PMN-PT materials attached to a target structure, ultrasonic waves at two distinctive frequencies are generated, and their modulation due to fatigue crack formation is detected. Furthermore, a reference-free NWMS algorithm is developed so that fatigue crack can be detected without relying on history data of the structure with minimal parameter adjustment by the end users. Then, the algorithm is embedded on FPGA, and the diagnosis is transmitted using a commercial telemetry system. An experimental verification has been performed using aluminum dog-bone specimens to show the feasibility of the developed active sensor node. Finally, the possibility of energy harvesting and RF power transmission is also explored for the self-sufficient operation of the wireless sensor unit.

9064-6a

Nonlinear effect of debonding of wafer type piezoelectric actuator on the behaviour of Lamb wave

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In Lamb wave based techniques for damage detection and material characterization, Piezoelectric Wafer (PW) transducers are often used for actuating Lamb wave. They offer advantages such as portability and, cost effectiveness. However, because of prolonged use, excessive voltage supply, or improper bonding onto the host structure, these PW actuators may get partially debonded from the host structure. In this paper, effect of this debonding on nonlinear behavior of Lamb wave manifested in the form of higher harmonics, is studied both experimentally and through finite element (FE) simulation. Augmented Lagrangian algorithm is used in FE simulation to solve the contact problem at the breathing debond. Three higher harmonics are observed in the experiments and also in the FE simulation. Signal processing schemes such as Morlet Wavelet Transform (MWT) and Hilbert Haung Transform (HHT) are implemented in the study and the results are reported in the paper. Nonlinearity parameter ? obtained from fundamental and second harmonics in the experiments and the simulation, is found to be increasing with increase in debonding area. This shows that actuator debonding brings in nonlinearity in the Lamb wave behaviour. Therefore, in material characterization or damage detection using Lamb wave based nonlinear techniques, the higher harmonics produced may get influenced by the false higher harmonics produced by actuator debonding, leading to incorrect results. Also these false higher harmonics resulting from actuator debonding may show illusory presence of defect or nonlinear elasticity in a pristine material, if bonding of actuator is not taken care of properly.

9064-7b

Evaluation of post-tensioning of a curved continuous girder using long-gauge fiber optic sensors

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Streicker Bridge is a pedestrian bridge on the Princeton University campus. It consists of a main span and four curved continuous girders (legs). The main span and the southeast leg of the bridge are equipped with fiber optic strain and temperature sensors, allowing the bridge to also function as an on-campus laboratory for the Structural Health Monitoring research group. Parallel sensors were embedded at critical cross-sections in the deck prior to the pouring of concrete. The deck of the southeast leg experienced early age cracking within a few days of concrete pouring, which was detected by the strain sensors. Post-tensioning was then performed and it is assumed that it closed off the cracks. Evaluation of post-tensioning forces is complex due to the existence of the cracks, and this paper researches a procedure to estimate the post-tensioning forces at cracked and uncracked locations. The obtained post-tensioning forces were compared to design forces and conclusions regarding the status of post-tensioning were made. This is important as it gives information on the actual health condition and performance of the structure. It also provides information on the safety of the structure. The objective of this paper is to present a methodology for the evaluation of the post-tensioning force along the deck based on strain measurements. The monitoring system, results, data analysis method, and conclusions regarding the bridge health condition and performance are presented in this paper.

9064-9b

Virtual test bed for a novel erosion monitoring system

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It is estimated that each year, roughly 60% of bridge failures in the U.S. are caused by water flowing around the bridge foundations. Although best practices for high flow estimation and foundation design are followed, the ability to accurately predict the physical factors associated with foundation scour still needs improvement. There is a need for a more precise understanding of the fluid-structure-soil interactions that lead to foundation scour as well as for a monitoring technique that can be used to validate and/or enhance scour modeling tools. Such a monitoring system would also help reduce bridge maintenance costs and enhance the safety of bridges.

The proposed work entails the development and calibration of computational modeling tools to simulate hydrodynamic sediment erosion and deposition processes around a bridge pier's that will be monitored using magnetostrictive and magnetic sensor arrays. The ongoing field observations under a DOT/RITA project provide a unique opportunity to compare numerical predictions to full-scale experiments, as well as comparisons with scaled-down physical laboratory flume experiments. Detailed model of unsteady flow around and through a bridge structure that incorporates simulation of both water and sediment at multiple scales is created using STAR-CMM+, a commercially available CFD software package that is particularly well suited for dynamic simulations involving flows with multiple phases. A computational mesh incorporating the geometry and properties of a selected case study site from the DOT/RITA project is implemented and refined. Boundary conditions and sensitivity to parameters are tested. Finally,

measurements using the data from field tests of the experimental sensor arrays for detecting the onset of hydrodynamic-induced soil erosion, are used to calibrate and fine-tune the Test Bed model to accurately represent the site.

9064-10b

A new approach for structural health monitoring by applying anomaly detection on strain sensor data

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Structural Health Monitoring (SHM) systems help to monitor critical infrastructures (bridges, tunnels, etc.) remotely and provide up-to-date information about their physical condition. In addition, it helps to predict the structure's life and required maintenance in a cost-efficient way. Typically, inspection data give insight in the structural health. The global structural behavior and predominantly the structural loading, is generally measured with vibration and strain sensors. Acoustic emission sensors are more and more used for measuring global crack activity near critical locations. In this paper, we present a procedure for local structural health monitoring by applying anomaly detection on strain sensor data for sensors that are applied in expected crack path. Sensor data is analyzed by automatic anomaly detection in order to find crack activity at an early stage. This approach targets the monitoring of critical structural locations, such as welds, near which strain sensors can be applied before use and/or inspection possibilities during use are limited. We investigate several anomaly detection techniques to detect changes in statistical properties, indicating structural degradation. The most effective one is a novel polynomial fitting technique, which tracks slow changes in sensor data. Our approach has been tested on a representative test structure (bridge deck) in a lab environment, under constant and variable amplitude fatigue loading. The results show an almost perfect crack detection for constant amplitude loading. In case of variable load, representing realistic traffic, high detection rates are achieved at low false positive rates. As a next step, the approach could be tested in a real life environment.

9064-11b

Bridge condition assessment from dynamic response collected using wireless sensor networks

AKM Anwarul Islam, Hiwa F. Hamid, Frank Li, Youngstown State Univ. (United States)

With a large inventory of deficient and aging bridges in the United States, this research focused on developing dynamic response based health monitoring system of prestressed box beam (PSBB) bridges that will provide more realistic and cost-efficient results. The hypothesis is based on the assumption that the health of a bridge is associated with its vibration signatures under vehicular loads. Two wireless sensor networks (WSNs) were deployed for the collection of real-time acceleration response of a 25-year old PSBB bridge under trucks with variable loads and speeds. The acceleration response of the bridge at its newest condition was collected from the dynamic simulations of its full-scale finite element (FE) models mimicking field conditions. The FE model was validated by field testing and numerical analysis. The acceleration data in time domain were transformed into frequency domain using Fast Fourier Transform to determine peak amplitudes and corresponding fundamental frequencies for the newest and current conditions of the bridge. The analyses and comparisons of the bridge dynamic response between the newest and current bridge interestingly indicate a 37% reduction in its fundamental frequency over 25 years of service life. This reduction is correlated to the current overall condition ratings of the bridge to develop application software for quick and efficient condition assessment of PSBB bridges. The application software can instantly calculate overall bridge condition rating when used with the WSN deployed on a PSBB bridge under vehicular loads. The research outcome and the software will help reduce bridge maintenance costs and will increase public safety.

9064-12b

Bridge load rating from dynamic response collected using wireless sensor networks

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This paper describes a method for load rating of prestressed box beam (PSBB) bridges based on their dynamic response collected using wireless sensor networks (WSNs). Although the percentage of deficient bridges in the United States has been declining slowly, a significant portion is still closed to traffic or posted with load restrictions. The precise load ratings of bridges are very expensive; therefore, new tools for quick, efficient and response-based load rating of bridges will save time and money. The hypothesis is based on the assumption that the health of a bridge is associated with its vibration signatures under vehicular loads. Two WSNs were deployed on a 25-year old PSBB bridge under trucks with variable loads and speeds for collecting real-time acceleration response at current condition. The acceleration response of the bridge at its newest condition was collected from the dynamic simulations of its full-scale finite element (FE) models mimicking field conditions. The FE model was validated by field testing and numerical analysis. Fast Fourier Transform and peak-picking algorithms were used to find the first bending mode frequency and its corresponding amplitude. This information and the necessary bridge geometric parameters were used to calculate the in-service stiffness of the bridge in order to develop application software for load rating of bridges. The application software can instantly calculate the overall bridge load rating when used with WSNs deployed on a PSBB bridge under vehicular loads. The research outcome and the software will help reduce bridge maintenance costs and will increase public safety.

9064-13a

Instantaneous wavenumber estimation for damage quantification in layered plate structures

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Guided wavefield detection is at the basis of a number of promising techniques for the identification and the characterization of damage in plate structures. Among the processing techniques that have been proposed for guided wavefield analysis, the estimation of instantaneous and local wavenumbers can lead to effective metrics that quantify the surface extent and the depth of delaminations in composite plates. Detailed characterization of realistic damage configurations, such as those resulting from impacts, often requires inspections at frequencies that are higher than those typically considered for guided wave interrogation, and that may be above the A1 mode cut-off. While this may be advantageous in terms of imaging resolution, it poses significant challenges due to the multi-modal content of the recorded signals.

This paper illustrates the application of instantaneous and local wavenumber damage quantification techniques for high frequency guided wave interrogation. The proposed methodologies can be considered as first steps towards a hybrid structural health monitoring/nondestructive evaluation (SHM/NDE) approach for damage assessment in composites. The challenges and opportunities related to the considered type of interrogation and signal processing are explored through the analysis of numerical data obtained using EFIT of damage in

CRFP plates. Realistic damage configurations are modeled from CT scan data on plates subjected to actual impacts, in order to accurately predict wave-damage interactions in terms of scattering and mode conversions. The simulated data contain all displacement components over a fine mesh over the surface of the plate and through the thickness. This wealth of data is utilized to enhance the information provided by instantaneous and local wavenumbers and mitigate the complexity related to the multi-modal content of the plate response. Signal processing strategies considered for this purpose include modal decoupling through filtering in the frequency/wavenumber domain, the combination of displacement components, and the exploitation of polarization information for the various modes as evaluated through the dispersion analysis of the considered plate lay-up sequence. The results presented assess the effectiveness of the proposed wavefield processing techniques as a hybrid SHM/NDE technique for damage detection and quantification in composite, plate-like structures.

9064-14a

Characterisation of CFRP surface contamination by laser induced fluorescence

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The application of Carbon Fibre Reinforced Polymers (CFRP) in aeronautics has been increasing. The CFRP elements are joint using rivets and adhesive bonding. The reliability of the bonding limits the use of adhesive bonding for primary aircraft structures, therefore it is important to assess the bond quality. The performance of adhesive bonds depends on the physico-chemical properties of the adhered surfaces. This research is focused on characterization of surfaces before bonding. In-situ examination of large surface materials, determine the group of methods that are preferred. The analytical methods should be non-destructive, enabling large surface analysis in relatively short time. In this work a spectroscopic method was tested that can be potentially applied for surface analysis. Four cases of surface condition were investigated that can be encountered either in the manufacturing process or during aircraft service. The first case is related to contamination of CFRP surface with hydraulic fluid. This fluid reacts with water forming a phosphoric acid that can etch the CFRP. Second considered case was related to silicone-based release agent contamination. These agents are used during the moulding process of composite panels. Third case involved moisture content in CFRP. Moisture content lowers the adhesion quality and leads to reduced performance of CFRP resulting in reduced performance of the adhesive bond. The last case concentrated on heat damage of CFRP. It was shown that laser induced fluorescence method can be useful for non-destructive evaluation of CFRP surface and some of the investigated contaminants can be easily detected.

9064-15a

A non-local finite difference scheme for simulation of wave propagation in composites

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The paper reports on a novel approach for the reduction of numerical dispersion introduced by finite difference discretization. Numerical dispersion results from time and spatial discretization of the governing equations and leads to reduced accuracy of simulations, which is aggravated by improper discretization time and length scales. Mesh refinements can mitigate such errors but lead to an increase in computation cost, which may be severe for proper simulation of transient wave propagation in elastic solids.

This paper presents a non-local finite difference scheme, which allows for considerable reduction of numerical dispersion. The scheme is based on finite difference coefficients that are derived through the approximation of the dispersion relation through Fourier series expansions. The approximation is based on the notion that the dispersion relations for a discretized domain are periodic in wavenumber space, where the Fourier series expansion is conducted. The coefficients of the series are directly related to the coefficients of high order, non-local finite difference schemes, and therefore directly define the interaction laws. Results are presented for two-dimensional domains in plane strain state, and of varying degree of anisotropy. Numerical dispersion mitigation is demonstrated for both longitudinal and shear wave modes propagating in different directions with respect to the mesh orientation. When available, results are compared with analytical solutions of initial value problems, or with the predictions of highly refined finite element simulations which are considered as reference results. The presented approach provides a systematic and physics-based methodology for the determination of coefficients for finite difference discretization schemes which provide enhanced accuracy in the prediction of wave motion in isotropic and non-isotropic media.

9064-16b

On the use of EMI for the assessment of dental implant stability

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The achievement and the maintenance of dental implant stability are prerequisites for the long-term success of the osseointegration process. Since implant stability occurs at different stages, it is clinically required to monitor an implant over time, i.e. between the surgery and the placement of the artificial tooth. In this framework, non-invasive tests able to assess the degree of osseointegration are necessary. In this paper, the electromechanical impedance (EMI) method is proposed to monitor the stability of dental implants. A 3D finite element model of a piezoceramic transducer (PZT) bonded to a dental implant placed into the bone was created, considering the presence of a boneimplant interface subjected to Young's modulus change. The numerical model was validated experimentally by testing bovine bone samples. The EMI response of a PZT, bonded to the abutment screwed to implants inserted to the bone, was measured. To simulate the osseointegration process a pulp canal sealer was used to secure the implant to the bone. It was found that the PZT's admittance is sensitive to the stiffness variation

of the bone-implant interface. The results are promising because they show the potential of EMI method to (i) evaluate the material properties around dental implant, and (ii) promote a novel non-invasive monitoring of dental implant surgical procedure.

9064-17b

A dual frequency transducer for intravascular ultrasound imaging

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Ultrasound imaging has been increasingly adopted in medical diagnosis, surgery guidanceand treatment assessment because of its relatively low cost, non-invasive and capability of real-time imaging. High frequency ultrasound is usually known with high resolution, although the high loss in two-way-loop at high frequency is known as the limitation. Compared to traditional medical ultrasonography, a new contrast-enhanced ultrasound (CEUS) provides an acceptable penetration depth by transmitting at low frequency (e.g. 3-7 MHz) and high frequency (> 20 MHz) echo receiving induced high resolution.

In this paper, a dual frequency transducer will be presented. This dual frequency transducer consists of a 6 MHz PMN-PT transmitting layer and a 40 MHz P(VDF-TrFE) receiving layer, and they share the same aperture. The 6 MHz layer generates a high pressure ultrasound wave to excite the introduced micro-bubbles. Then the high frequency echo (> 30 MHz) of the nonlinear response from the micro-bubbles will be received by theP(VDF-TrFE) layer. As a result, the high resolution, high signal to noise ratio imagingat a relatively large depth can be achieved.

Initial study shows that 6 MHz element can be used to transmit acoustic waves with pressure >1.5MPa under 200 Vp-p, which is high enough to induce non-linear response from micro-bubbles. P(VDF-TrFE) receiving element, which has its own high attenuation backing to restrain the wave ringing and internal echoes, was designed with the expected -6 dB bandwidth over 100 %. This dual frequency transducer is being fabricated and the detailed test results will be reported in the full paper.

9064-18b

Speed of sound in red blood cells determined from the acoustic phase images

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In scanning acoustic microscopy with phase contrast (PSAM), the respective phase variations provide information to determine the topography of the objects under investigation. This is achieved for homogeneous samples with slow variations in their surface structures with respect to the lateral resolution of the acoustic microscope. The time of flight (TOF) is used to determine distances along an object traversed by the ultrasound if the speed of propagation of the ultrasound in that object is known and vice versa for a known geometry, the speed of propagation can be derived. With a prior determined thickness, obtained from AFM measurement, the speed of sound is determined for fixated red blood cells on glass substrates as a key parameter that can be used to quantify the mechanical properties.

9064-19a

Optical controller for 3D manipulation

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A 3D controller is a device that can operate the dimensions of X, Y and Z. A typical 3D controller consists of a two dimensional controller with a superfluous knob for its third dimension. In this paper, a 3D controller that follows a real-dimensional setup is described. The proposed controller incorporates all three dimensions into a single controller allowing for further utility while decreasing complexity for its user. To achieve this goal, our design is based on an optical method called “quad shear sensing”. The setup comprises of infrared (IR) sensors mounted on a fixed platform and an IR emitter mounted on a sliding framework. The IR sensors are placed in a square arrangement to detect the IR light emitted from the IR light source attached to the sliding framework. Each sensor will read out different values of voltage depending on the relative position of the IR light source from each of the sensor. These values are then calculated with pre-determined formulas to determine the position of the light source and therefore the position of the controller. On this controller, there are a total of eight sensors arranged in two squares – one larger square surrounding the other. Eight sensors were used in accordance with the quad shear sensing technique to enlarge the area of possible movement. A prototype controller is built and it successfully demonstrates the ability to truly utilize all three dimensions in a single motion of the interface. Our proposed optical controller allows for high precision controlling in many circumstances because of its direct mapping of motion. Adding in force feedback, the optical controller will be provide realistic manipulation

9064-20a

Robust evaluation of time series classification algorithms for structural health monitoring

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Structural health monitoring (SHM) systems provide real-time damage and performance information for civil, aerospace, and mechanical infrastructure through analysis of structural response measurements. Active approaches to SHM in both the vibration and ultrasonic domain require design of an appropriate excitation signal. Previous work has shown the benefit of tailoring excitation signals through an optimization process to improve damage detectability. In this work, optimal signal design is accomplished by a custom genetic programming method. Signal generation algorithms are evolved based on a damage detection performance based fitness measure. The authors have previously demonstrated success of a similar genetic programming system for automated feature extraction algorithm design called Autofead. The proposed method is experimentally validated through benchmarking simulations and hardware-in-the-loop actuation signal design for active sensing. The optimal excitation is shown to be dependent on the selected damage feature suggesting further gains by combining the proposed method with Autofead to coevolve excitation signals and feature extraction algorithms.

9064-21a

Ultrasonic structural health monitoring based on wide band excitation schemes

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Wide band ultrasonic excitation schemes allow the detection of the time of flight avoiding the normally experienced modulo 2π uncertainties involved in narrow band phase detection. In addition pulse compression and spectroscopic monitoring can be performed. The developed techniques allow furthermore high resolution monitoring at low power levels. Detection schemes including essential parts of the instrumentation are demonstrated and applications in structural health monitoring are presented.

9064-22a

Laser Doppler velocimeter using dual-core photonic crystal fiber

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The Laser Doppler velocimeter (LDV) is a widely accepted tool for fluid dynamic investigations in gases and liquids, extensively used in many fields. As a sensor system, the LDV possesses many advantages, including essentially non-intrusive pattern, good spatial and temporal resolution, high accuracy and easy application in hostile environments. A single fiber is the optimal configuration of a miniaturized LDV probe; however, this would require a reference beam, with the single fiber both emitting and collecting the optical signal. This setup enlarges the angle between two incident beams and limits the measurement volume in the macro fluid channel, which is appropriate for measuring the velocity component parallel to the fiber axis. Many investigators have demonstrated a technique using a two-fiber beam transmission based on the differential pattern, which enables velocity measurement perpendicular to the fiber axis.

In this paper, we present an improved version of the design by using a Dual-core photonic crystal fiber (DC-PCF) and carry out a more rigorous theoretical and experimental study of this technique. We will investigate the differential velocity measurement principle and demonstrate flow measurement using the proposed DC-PCF fringe projection interferometer technique. The output velocity signals will be analyzed using a special signal processing algorithm. Some of the crucial factors in determining the velocity measurement will be discussed and the experimental results will be compared and verified using a light gate sensor.

9064-23a

Evaluation of different scintillators for 1MV NDE x-ray imaging

George Zentai, Arundhuti Ganguly, Gary Visrshup, Varian Medical Systems, Inc. (United States)

X-ray radiography is an important and frequently used NDE method of testing metal structures, such as tube welding quality, cracks and voids in cast iron or other metals. It gives fast and visible answer for structural defects. The Varian high energy portal imagers used at high energy cancer treatment Clinacs have a 1mm thick Cu build-up plate on top of the Gadox scintillator to improve the absorption at high energy. We compared the traditional Gadox screen with and without this Cu plate, tested different hybrid scintillators, which consisted of different phosphor layers deposited onto a fiberoptic plate. Other screen tested was a 2cm thick fiberoptic plate which contained scintillating fibers. The sensitivity (number of digital counts per a given X-ray dose), the resolution (MTF – modulation transfer function) and the DQE (detective quantum efficiency) were compared of these X-ray conversion screens.

We found that the additional 1mm Cu plate, which improves the absorption and the contrast at 6 or higher energy MeV imaging, does not improve the image quality at 1MV rather it attenuates the X-rays, so we got lower sensitivity and lower DQE(0) of 7% with the additional Cu plate than without ~10% .

The evaporated scintillators on fiberoptic plates, we tested, were too thin so we did not get enough sensitivity from these screens. The best results came from the thick scintillating fiberoptic screens, which provided the best DQE and high resolution at 1MV X-ray beam. Further optimization is planned by changing the thickness of the scintillating fiberoptic plate.

9064-24a

The electromechanical design of a self-assemble robot array

Wei-Chih Wang, Univ. of Washington (United States)

This paper describes the method of using wirelss microcontroller to build an autonomous system which is made of self-assembly blocks. At first, the mechanical design is briefly reviewed. Each cubic block has six faces; each attached on an arm with worm gear and it is driven by a motor. The motors are controlled by a single microcontroller (Arduino UNO) through two H-bridge chips. Then the electrical part is detailed including circuits, program frame, different wireless communication methods and magnetic latching with shape memory alloy. Two blocks can communicate with each other through the wireless chip on the microcontroller and cooperate to complete a pre-defined goal. The basic idea is to use microcontroller controlled blocks to build an autonomous system of blocks capable of assembling themselves into various configurations. This kind of assembly block system can be applied to many areas, such as smart building structure and large storage system.

9064-25a

Anomaly detection in heterogeneous media via saliency analysis of propagating wavefields

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This work investigates the problem of anomaly detection in highly heterogeneous media by means of an agnostic inference strategy based on the concepts of spatial saliency and data sparsity. Specifically, it addresses the implementation and experimental validation aspects of a methodology for salient feature extraction in two-dimensional wavefields that was recently proposed for laser-based diagnostics, and that leverages the wavefield spatial reconstruction capability featured by scanning laser vibrometers. The methodology consists of two steps. The first is a spatiotemporal windowing strategy designed to partition the structural domain in small sub-domains and replicate impinging wave conditions at each location. The second is the construction of a low-rank-plus-outlier model of the regional data set using principal component analysis. Regions are labeled salient when their behavior does not belong to a common low-dimensional subspace that successfully describes the typical behavior of the anomaly-free portion of the surrounding medium. The most attractive feature of this method is that it requires virtually no knowledge of the structural and material properties of the medium. This property makes it a powerful diagnostics tool for the inspection of media with high heterogeneity, or with unknown or unreliable material property distributions, e.g., as a result of severe material degradation over large portions of their domain. The objective of this work is to test the agnostic capability of the method, by checking its robustness against cases characterized by extreme material non-idealities, where conventional triangulation methods based on the pitch-catch or pulse-echo paradigms would fail.

9064-27b

Robust modal curvature features for identifying multiple damage in beams

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An intrinsic deficiency of curvature mode shape is its susceptibility to measurement noise, easily impairing its advantage of sensitivity to multiple damage. To overcome this drawback, this study focuses on a synergy between a wavelet transform (WT) and a Teager energy operator (TEO), termed TEO-WT curvature mode shape, to improve the curvature mode shape. Compared to the conventional curvature mode shape, the TEO-WT curvature mode shape features greater sensitivity to damage and stronger immunity to noise. The TEO-WT curvature mode shape is first verified with various analytical cases in noisy environments, and then experimentally validated by detecting multiple cracks in steel beams with mode shapes acquired by a scanning laser vibrometer. The analytical and experimental results shows that the proposed curvature mode shape has strong capability in effectively detecting slight multiple cracks in beams with noise robustness, providing an effective approach for identifying complicated damage in structures.

9064-28b

Sideband frequency response function based damage identification of rotor system with open cracks

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This paper develops a new vibration based damage detection method to identify the location and severity of structural damage of periodically time-varying systems. The frequency response function (FRF) shifts induced by cracks are utilized to detect the location, depth and orientation angle of open transverse cracks on a shaft-disk system. The dynamical model of system is built based on the Lagrange principle and the assumed mode method while the crack model for periodically time-varying systems is based on the fracture mechanics. This method provides the advantages of arbitrary interrogation frequency and multiple inputs/outputs which greatly enriches the dataset for damage identification. According to our analysis, three damage parameters are needed to represent and estimate the depth and orientation angle of an open crack on a rotor system. Furthermore, it is found that an open crack will lead to the appearance of sidebands in the FRF curve of damaged system. The damage identification algorithm integrates the least square method and Newton Raphson method to iterate the damage parameters. Finally, the method is synthesized via harmonic balance and numerical examples for a shaft/disk system to demonstrate the effectiveness in detecting both location and severity of the structural damage. The location and severity of multiple cracks are identified using FRF shifts excited by three categories of interrogating frequency: near-resonance, near-sidebands and far-off-resonance. The results shows that near-sidebands interrogation can be an effective way to detect the damage existed on periodically time-varying systems.

9064-29b

Bayesian prognosis of bearing condition using vibration-based monitoring data

Zhu Mao, Michael D. Todd, Univ. of California, San Diego (United States)

To avoid in-situ catastrophic failure of various sorts of machinery, condition-based monitoring (CBM) is increasingly adopted to provide an early warning of system defects and, if possible, determine remaining useful life (RUL) given the current status and future loadings. Bearings are one of the most critical components in rotating machines, and offline inspection in a time-based fashion is not always feasible depending on the specific application. Moreover, most of the current prognosis models are based upon physics-intuitive algorithms, such as Paris' Law, and estimate the nominal operational life, usually in terms of L10, yet the actual RUL under heavy operational and environmental complexity expands a wide range. Consider the huge uncertainty of nominal life and the lack of a physics model with in-situ data, this paper proposes a CBM data-driven model to characterize the vibration data, and a Bayesian framework is deployed to fuse the monitoring data, with contaminated noise, to a nonlinear drift Wiener process data-driven model. With the time prediction of vibration, a condition-based threshold can be selected based on specific operations, and the uncertainty associated with the RUL prediction is also available through the recursive model updating. A SpectraQuest machinery fault simulator is used to generate bearing data for model validation, and foreign particles, lubrication leakage, and surface corrosion are the three damage types adopted in this paper.

9064-30b

Continuous fatigue assessment of offshore wind turbines using stress prediction technique

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Offshore wind turbines, due to their continuous subjection to cyclic loading caused by wind and wave excitation forces, exhibit high periodic stresses and strains at critical locations leading to structural failure. Therefore, fatigue assessment is an issue of essential importance. Fatigue assessment includes estimation of the expected damage accumulation and the remaining life-time of the structure. This work is based on output-only vibration measurements at limited number of locations provided by a sensor network installed on the structure. The stress-strain response histories at the accessible points of the structure can be directly obtained by post-processing the available sensor data. However, this is not the case for critical locations which are not accessible for direct measurements. The Operational Modal Analysis (OMA) based on Modal Expansion can provide a prediction about the stress-strain responses in every point of the structure. The methodology is based on the use of a Finite Element numerical model for the prediction of the stress-strain responses, whose modal parameters are identified by the Operational Modal Analysis and the acceleration time histories recorded at several points of the structure. The expected fatigue damage accumulation can be obtained either by using time domain techniques (rain-flow counting) or frequency domain techniques based on the Dirlik approximation. Both techniques make use of the stress response time histories. In the time domain only the stress time history signal is needed whereas in the frequency domain the Power Spectral density of the stress process is used.

9064-32b

Vibration-based structural health monitoring using adaptive statistical method under varying environmental condition

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It is well known that the dynamic properties of a structure such as natural frequencies depend not only on damage but also on environmental condition (e.g., temperature). The variation in dynamic characteristics of a structure due to environmental condition may mask damage of the structure. Without taking the change of environmental condition into account, false-positive or negative damage diagnosis may occur so that structural health monitoring becomes unreliable. In order to address this problem, an approach to construct a numerical model (i.e., a regression model) based on structural responses considering environmental factors has been usually used by many researchers. The key to success of this approach is the formulation between the input and output variables of regression model to take into account the environmental variations. Environmental factors such as temperature, humidity are used as the input of regression model. However, it is quite challenging to determine proper environmental variables and measurement locations in advance for fully representing the relationship between the structural responses and the environmental variations. One alternative is to remove the variations caused by environmental factors from the structural responses by using statistical approaches (e.g., principal component analysis (PCA), factor analysis, etc.). However, the performance of this method is depending on how to define the reference data set. Generally, there is no prior information on reference condition (i.e., healthy condition) during data mining. The reference condition is determined based on subjective perspective with human-intervention. To overcome this, the paper proposes a novel adaptive statistical method for monitoring of structural damage detection under environmental change. The proposed method is not required to determine the reference condition and measure the environmental variables. On the other hand, it adaptively reflects new

observations to update the reference condition. The proposed method is tested on numerically simulated data for a range of noise in measurement under environmental variation. A comparative study with other statistical analysis methods demonstrates the superior performance of the proposed method for structural damage detection.

9064-33b

Vibration test and health monitoring of membrane structure using non-contact laser excitation

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Membranes are widely used in some fields of engineering because their properties such as thin, light, flexible, and translucency give some benefits to engineering applications. From this background, structural health monitoring of membrane structure has become one of important research topics in mechanical engineering to ensure the proper function of membrane structure. In this paper, a vibration testing and health monitoring system based on an impulse response excited by laser is proposed to detect damage on membrane structure. A high power Nd: YAG pulse laser is used to generate an ideal impulse on a membrane structure by applying shockwave generated by laser-induced break down in air. A health monitoring apparatus is developed with this vibration testing system and a damage detecting algorithm which only requires the vibration mode shape of the damaged membrane. The artificial damages are applied to membrane structure by cutting and tearing the membrane. The vibration mode shapes of the membrane structure which got from vibration testing by using laser-induced breakdown and laser Doppler vibrometer are then analyzed by 2-D continuous wavelet transformation. The location of damages is indicated by the dominant peak of wavelet coefficient which can be seen clearly by applying the boundary treatment and the concept of iso-surface to 2-D wavelet coefficient. The effectiveness of the present approach is verified by finite element analysis (FEA) using ANSYS 14.0 and experimental results, demonstrating the ability of the method to detect and identify the positions of damages on the membrane structure.

9064-34a

Non-contact high speed ultrasonic guided wave inspections of rails

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The University of California at San Diego (UCSD), under a Federal Railroad Administration (FRA) Office of Research and Development (R&D) grant, is developing a system for high-speed and non-contact rail integrity evaluation. A prototype using an ultrasonic air-coupled guided wave signal generation and air-coupled signal detection, in pair with a real-time statistical analysis algorithm, is under development. This system requires a specialized filtering approach due to the inherently poor signal-to-noise ratio of the air-coupled ultrasonic measurements in rail steel. Various aspects of the prototype have been designed with the aid of numerical analyses. In particular, simulations of ultrasonic guided wave propagation in healthy and defected rails have been performed using a Local Interaction Simulation Approach (LISA) algorithm. Many of the system operating parameters were selected based on Receiver Operating Characteristic (ROC) curves, which provide a quantitative manner to evaluate different detection performances based on the trade-off between detection rate and false positive rate. Experimental tests have been carried out at the UCSD Rail Defect Farm. The test results indicate that the prototype is able to detect internal rail defects with a high reliability. A field test will be planned later in the year to further validate these results. Extensions of the system are planned to add rail surface characterization to the internal rail defect detection.

9064-35a

On the processing of Leaky guided waves propagating in immersed plates

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We present a non-destructive inspection method for the structural health monitoring of underwater structures. A laser operating at 532 nm is used to excite leaky guided waves on an aluminum plate immersed in water. The plate has a few artificial defects namely vertical notch, horizontal notch, corrosion, and small hole. An array of five immersion transducers allocated in a half-moon platform is used to detect the propagating waves. Two different signal processing techniques are implemented to assess the presence of damage. The first method is based on continuous wavelet transform to extract a few damage-sensitive features that are used in a multivariate analysis. The second approach uses the same features to lead on artificial neural network for damage classification. In this paper, the results from both methodologies are presented and compared.

9064-36b

Combined electromechanical impedance and fiber optic diagnosis of aerospace structures

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Electromechanical impedance is a popular diagnostic method for assessing structural conditions at high frequencies. It has been utilized, and shown utility, in aeronautic, space, naval, civil, mechanical, and other types of structures. In contrast, fiber optic sensing found its niche in static strain measurement and low frequency structural dynamic testing. Low frequency limitations of the fiber optic sensing are mainly governed by its hardware elements, and as hardware improves, so does the bandwidth (frequency range x number of sensors). In this contribution we demonstrate simultaneous high frequency measurements using fiber optic and electromechanical impedance structural health monitoring technologies.

A laboratory specimen imitating an aircraft wing structure, incorporating surfaces with adjustable boundary conditions, was instrumented with piezoelectric and fiber optic sensors. Experiments were conducted at different structural boundary conditions associated with deterioration of structural health. High frequency dynamic responses were collected at multiple locations on a laboratory wing specimen and conclusions were drawn about correspondence between structural damage and dynamic signatures as well as correlation between electromechanical impedance and fiber optic sensors' spectra. Theoretical investigation of the effect of boundary conditions on electromechanical impedance spectra is presented and connection to low frequency structural dynamics is suggested. It is envisioned that acquisition of high frequency structural dynamic responses with multiple fiber optic sensors may open new diagnostic capabilities for fiber optic sensing technologies.

9064-37b

New applications of a model of electromechanical impedance for SHM

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The report focuses on the further development of the model of the electromechanical impedance (EMI) of the piezoceramics transducer (PZT) embedded to an aircraft structural element, and its application for aircraft structural health monitoring (SHM). The model proposed a year ago at the SPIE conference (Proc. of SPIE Vol. 8694 869410-1-14), based on the modal decomposition and involves direct evaluation of the dynamic properties (eigenfrequencies and eigenmodes).

Two versions of the possible applications to be drown from the general theory are discussed. The first version is based on a separate numerical simulation of modal displacements at the contact surface of PZT and the structural element under harmonic excitation. Distributed interaction forces between a transducer and host structure due to the condition of compatibility as a result of the numerical solution of linear algebraic equations. The second version involves direct determination of modal characteristics of the "transducer - host structure". In this case the definition of the relative increment of the amplitude of the contact surface area has key significance. The same parameter can serve as a filter of the relative importance of the different eigenmodes.

The validity of the model is confirmed by experimental studies. In particular, the EMI change of 1 mm thick plate of Al2024-T6 with PZT as a function of the fatigue crack size is compared with the predicted response.

9064-38a

Modeling GW generation, propagation, and sensing in LISA

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Damage prognosis plays a critical role in ensuring the functionality and cost effective maintenance of modern engineering structures. Structural health monitoring (SHM), an important component of damage prognosis systems, is responsible for detecting the presence and location of defects in structures. Guided wave (GW) techniques are one of the most desirable methods for SHM due to their ability to propagate over long distances with minimal attenuation and their sensitivity to a variety of damage types. Development of robust SHM systems for damage prognosis requires a comprehensive understanding of wave generation and propagation characteristics in different structure media.

Accurate and efficient modeling of GW is essential to understand and predict the wave generation and propagation characteristics. An analytic 3-D elasticity-based formulation would be intricate for modeling practical structures because of the interface conditions and complex geometry. Traditional numerical methods like finite element (FE) analysis are computationally inefficient because of the small wavelength discretization required to attain converged results.

Numerical simulations can be accurately and effectively done using the local interaction simulation approach (LISA) to characterize the generation and propagation of GW in isotropic and composite plates. In the past, GW simulations using LISA have been conducted using prescribed input displacements to model the actuation of the piezoelectric transducers. In the proposed paper, a piezo-coupled LISA formulation will be presented to model piezoelectric transducers as an integral part of the formuation. The new approach will incorporate both mechanical and electrical coupling between the piezo transducers and the substrate. From this new formulation, GW generation in isotropic and composite plates will be investigate, and in particular the role of the transducer modeling effects when simulating piezoelectric effects in LISA. Moreover, the mechanical response of the piezo actuator to prescribed potential and the piezo sensor response to the propagating GW will be explored.

9064-39a

Predictive modeling of power and energy of guided waves in anisotropic composites excited by PWAS

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This paper is extension of our previously presented work on the use of exact Lamb wave modes for modeling power and energy transfer between PWAS and the hosted structures. The current study presents a theoretical development for power and energy transduction between piezoelectric wafer active sensor (PWAS) and anisotropic composite structures. Our focus is on unidirectional and multilayered unidirectional composites. Modeling the propagation of elastic wave energy in anisotropic medium is a challenging process because the energy direction differs in general from that of the wave front. This situation leads to differences in magnitude and direction between phase and group velocities; quantities that need to be well known for any structural health monitoring (SHM) based on guided wave propagation in composites. We used transfer matrix method (TMM) to get our dispersion curves for unidirectional and multilayered unidirectional case studies. We applied the stiffness matrix method (SMM) to have our solution without numerical instability that usually is a limitation of TMM.

Normal mode expansion (NME) technique was used in our models of power and energy and the model assumes perfect bonding (pin-force) between the PWAS and the structure. NME technique was used instead of integral transform techniques (ITT) because the ITT gets very complex for anisotropic cases, while the NME can be used for isotropic or generally anisotropic layers. The difference between isotropic or anisotropic NME lies mainly in the nature of the modeshapes. Therefore, NME can be considered more general than ITT. Simulations for kinetic energy and strain energy densities are presented and it is shown that they are equal, as expected from the Reciprocity Theorem. The paper ends with summary, conclusion, and suggestions of future work.

9064-40a

WFR-2D: an analytical model for PWAS-generated 2D ultrasonic guided wave propagation

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This paper presents an analytical model for the simulation of PWAS-generated 2-D ultrasonic guided wave propagation and interaction with damage. The design of structural health monitoring systems requires computationally-efficient predictive modeling tools that can provide wide parameter space exploration on sensor dimension, location, guided wave characteristics (mode type, frequency, wavelength, etc.) to achieve best detection and quantification of certain types of damage. Such parameter space exploration desiderate can be best satisfied with analytical tools which are fast and efficient.

An analytical model was constructed based on the exact 2-D Lamb wave solution. Lamb waves generated by the transmitter piezoelectric wafer active sensor (PWAS) propagate into the structure, interact with damage, undergo scattering and mode conversion, and are picked up by the receiver PWAS. The damage effect is inserted in the model by considering the damage as a secondary wave source with directivity scattering coefficients which have to be determined elsewhere. Our analytical procedure was coded into MATLAB, and a predictive simulation tool called WaveFormRevealer 2-D (WFR-2D) was developed. The WFR-2D analytical simulation results were compared with multiphysics finite element models and experiments. First, multimode Lamb wave propagation in a pristine aluminum plate was simulated with WFR-2D, compared with finite element model, and verified by experiments. Then, an inhomogeneity was machined into the plate to represent damage.

Analytical modeling and finite element simulation were carried out, and finally compared with the experimental results. The paper finishes with summary, conclusions, and suggestions for future work.

9064-41a

Use of augmented reality in aircraft maintenance operations

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This paper proposes an Augmented Reality (AR) strategy in which a Lamb waves based impact detection methodology dynamically interacts with an head portable visualization device allowing the inspector to see the estimated impact position (with its uncertainty) and impact energy directly on the plate-like structure. The impact detection methodology uses a network of piezosensors bonded on the structure to be monitored and a signal processing algorithm (the Warped Frequency Transform) capable to compensate for dispersion the acquired waveforms. The compensated waveforms yield to a robust estimation of Lamb waves difference in distance of propagation (DDOP), used to feed hyperbolic algorithms for impact location determination, and allow an estimation of the uncertainty of the impact positioning as well as of the impact energy. The outputs of the impact methodology are passed to a visualization technology that yielding their representation in Augmented Reality (AR) is meant to support the inspector during the on-field inspection/diagnosis as well as the maintenance operations. The inspector, in fact, can see interactively in real time the impact data directly on the surface of the structure. To validate the proposed approach, tests on an aluminum plate are presented. Results confirm the feasibility of the method and its exploitability in maintenance practice.

9064-42a

Vibro-acoustic 3D FE simulations to validate a SAFE-BEM formulation for leaky waves computation

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In this work, vibroacoustic three-dimensional finite element simulations are performed with the aim of validating a recently developed formulation for the computation of leaky guided waves propagating in waveguides surrounded by fluids. The above formulation couples a mesh of semi-analytical finite elements (SAFE), to discretize the waveguide cross-section, with a mesh of boundary elements (BEM) along the contour of the waveguide cross section, to model the unbounded outer fluid domain. As a result, dispersion curves for leaky and non-leaky guided waves existing in waveguides of irregular cross-section immersed in an ideal fluid can be computed.

To validate such formulation, dedicated finite element simulations are performed and the resulting time-transient waveforms analysed via the 2D Fast Fourier Transform to extract the frequency-wavenumber energy content of the propagating waves. Such information is compared with the predicted dispersion curves to validate the mentioned SAFE-BEM formulation.

Effective time-transient simulations of stress and pressure waves are carried out using a in-house developed Lagrangian Finite Element code. The code describes both fluids and solids, and employs displacement-based finite elements and a centered difference time-stepping algorithm to handle damping accurately and efficiently. Absorbing boundary conditions are applied to simulate the unbounded fluid domain. Robust performance for materials with limited compressibility is achieved using incompatible-mode brick elements. The code can handle models of hundred millions of elements exceeding capabilities of commercially available FEM codes.

An application on L-shaped waveguides is proposed and some final considerations on the comparison of the extracted and predicted dispersion curves close the paper.

9064-43a

Improved damage imaging in aerospace structures using a piezoceramic hybrid pin-force wave generation model

Pierre-Claude Ostiguy, Nicolas Quaegebeur, Patrice Masson, Univ. de Sherbrooke (Canada)

The correlation-based imaging technique called « Excitelet » is based on guided wave generation and sensing using a sparse or compact piezoceramic array and the measurement of reflections induced by potential damage. The method uses a wave propagation model to generate a library of signals which are then correlated with the measured signals to perform imaging using Full-Matrix Capture. In this paper, a hybrid pin-force model is incorporated into the wave propagation model for modeling the interaction between the piezoceramic transducer and the host structure.

In the hybrid pin-force model, the shear stress at the edges of the piezoceramic is considered to vary as a function of the frequency, allowing a better representation of the transducer dynamics and complex interaction between guided waves and transducers.

The imaging technique is experimentally validated on a riveted aluminum lap-joint representative of an aircraft component subjected to traction fatigue tests. This structure is instrumented with a linear array of 8 circular elements of 3 mm diameter each. The sample is then submitted to fatigue cycling on a test machine. Imaging results obtained using both A0 and S0 modes below 500 kHz are presented for various crack lengths. It is demonstrated that the crack tip can be accurately detected, as the correlation level is related to the crack size. The standard pin-force formulation is compared to the improved hybrid pin-force model, for an excitation over a wide frequency band. The results demonstrate the interest of using the improved wave generation model for damage imaging in aerospace structures.

9064-44b

Characterisation of CFRP adhesive bonds by electromechanical impedance

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In aircraft industry the Carbon Fibre Reinforced Polymer (CFRP) elements are joint using rivets and adhesive bonding. The reliability of the bonding limits the use of adhesive bonding for primary aircraft structures, therefore it is important to assess the bond quality. The performance of adhesive bonds depends on the physico-chemical properties of the adhered surfaces. The contamination leading to weak bonds may have various origin and be caused by moisture, release agent, hydraulic fluid, fuel, poor curing of adhesive and so on. In this research three different causes of possible weak bonds were selected for the investigation: 1. Weak bond due to release agent contamination, 2. Weak bond due to moisture contamination, 3. Weak bond due to poor curing of the adhesive. In order to assess the bond quality electromechanical impedance (EMI) technique was selected and investigation was focused on the influence of bond quality on electrical impedance of piezoelectric transducer. The piezoelectric transducer was mounted at the middle of each sample surface. Measurements were conducted using HIOKI Impedance Analyzer IM3570. Using the impedance analyzer the electrical parameters were measured for wide frequency band. Due to piezoelectric effect the electrical response of a piezoelectric transducer is related to mechanical response of the sample to which the transducers is attached. The impedance spectra were investigated in order to find indication of the weak bonds. These spectra were compared with measurements for reference sample using indexes proposed in order to assess the bond quality.

9064-45b

Small-factor electromechanical impedance measurement board for space applications

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Recent advancements in electronics has dramatically improved form factor of the electromechanical impedance (EMI) measurement hardware. Electronic implementations of such devices range from simple measurement circuits collecting amplitude response only to phase/gain measurements with high accuracy. This contribution discusses development, fabrication and testing of a small-factor electromechanical impedance board for collection of electromechanical signatures in demanding space environment. Power and bandwidth requirements are inferred from the necessity of the circuit to autonomously function during spaceflight and perform electromechanical impedance measurements in frequency ranges typical to EMI applications. Amplitude and phase measurements circuits utilized off-the-shelf components and a popular microcontroller. The impedance is inferred from the response of the electronic circuit yielding impedance amplitude and phase, which are subsequently digitized by the microcontroller for further processing and achieving. The measurement results in a data file containing impedance amplitude and phase at a particular interrogation frequency. Results of the small-factor EMI measurement board were compared to standard and portable impedance analyzers and conclusions were drawn on performance characteristics of the new device.

9064-46b

Effects of temperature variations on piezoelectric sensor diagnostics process based on impedance measurements

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A sensor diagnostic and validation process that performs in-situ monitoring of the operational status of piezoelectric (PZT) active-sensors in structural health monitoring (SHM) applications is presented. The basis of this process is to track the changes in the capacitive value of piezoelectric materials, which shows up in measured admittance. Both degradation of the mechanical/electrical properties of a PZT transducer and the bonding defects between a PZT patch and a host structure could be identified by the proposed process. Due to the temperature dependent nature of piezoelectric materials, we investigated the effects of temperature on sensor diagnostic process. The effect of temperature found to be remarkable, modifying the measured capacitive values significantly. This results indicates that there is need for developing a rigorous signal processing technique to normalizing the temperature effects. It has been also found that, as the temperature changes, the sensor diagnostic process was influenced not only by a sensor and a structure, but by a bonding materials that was used for attaching a piezoelectric transducers to a structure, which would be an important characteristic when designing an SHM system. This paper summarizes considerations needed to develop such sensor diagnostic processes, experimental procedures and results, and additional issues that can be used as guidelines for future investigations.

9064-47b

Uncertainty propegation and analysis in structural health monitoring

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SHM is a rapidly growing field of research due to the low relative cost and the information via non-destructive means. An analysis of how SHM sensors and data withstood to variation in parameters and repeatability was performed. The sensors used were Metis Design's intelli-connector™ nodes. A Type-A uncertainty analysis was performed in the guided wave setting while sweeping through three parameters: driving voltage, driving frequency, and number of averages taken. The error in the peak magnitude and time, and the error in the calculated wave speed were the reported errors. The largest source of error was due the number of averages taken. As the number of averages increase, the error associated decreases due to the law of large numbers. This can account for about 1% error on the peak magnitude. The error associated with the peak time was a combination of two experiments. The first experiment took a look at the time variance of the peak due to error in the peak magnitude. The second experiment was done using the same parameters but performing the same test many times. The aggregate error associated with the peak time is 0.15 μs. The accuracy calculations for the wave speed were well managed for the majority of the parameter variation but did have a large error near the extremes of the driving frequency range. The errors measured and calculated were small compared to the raw data but can be significant when applying techniques such as damage detection and loose bolt determination.

9064-48b

Towards monitoring of acoustic emission activity using thin wafer piezoelectric sensor

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Acoustic emission is a well-known technique for monitoring onset and propagation of material damage. The technique has demonstrated utility in assessment of metallic and composite materials in applications ranging from civil structures to aerospace vehicles. While over the course of few decades AE hardware has changed dramatically, sensors have seen little changes. Traditional acoustic emission sensor solution utilizes a thickness resonance of the internal piezoelectric element which, coupled with internal amplification circuit, results in relatively large sensor footprint. Thin wafer piezoelectric sensors are small and unobtrusive, but have seen limited AE applications due to low signal-to-noise ratio and other operation difficulties. In this contribution, issues and possible solutions pertaining utility of thin wafer piezoelectrics as AE sensors are discussed. Results of AE monitoring of fatigue damage using thin wafer piezoelectric and conventional AE sensors are presented.

9064-49a

Guided ultrasonic waves for impact damage detection in composite panels

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Carbon fiber laminate composites, consisting of layers of polymer matrix reinforced with high strength carbon fibers, are increasingly employed for aerospace structures. They offer advantages for aerospace applications, e.g., good strength to weight ratio. However, impact during the operation and servicing of the aircraft can lead to barely visible and difficult to detect damage. Depending on the severity of the impact, fiber and matrix breakage or delaminations can occur, reducing the load carrying capacity

of the structure. Efficient structural health monitoring of composite panels can be achieved using guided ultrasonic waves propagating along the structure. Impact damage was induced in the composite panels using standard drop weight procedures. The guided wave scattering at the impact damage was measured using a noncontact laser interferometer, quantified, and compared to baseline measurements on undamaged composite panels. Significant scattering of the A0 guided wave mode was observed, allowing for the detection of barely visible impact damage. The impact damage was further characterised using standard ultrasonic C-scans. The guided wave scattering was modelled using full three-dimensional Finite Element (FE) simulations, and the influence of the different damage mechanisms investigated. Good agreement between experiments and predictions was found. The sensitivity of guided waves for the detection of barely visible impact damage in composite panels has been verified.

9064-50a

Theoretical solution for response of surface bonded rectangular piezoelectric actuators/ sensors to Lamb waves

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Using Lamb waves generated by piezoelectric actuators is among the most promising methods in structural health monitoring (SHM) due to massive plate-like engineering structural parts and feasibility of real-time non-destructive detecting. Existing theoretical studies ignored the coupling between piezoelectric sensors and plate, thus simplified the force between them to be unit force, and their results only compares the shape, yet not the amplitude, of the experimental output and theoretical output. It is hoped that this work would fill this void. The work is to derive a closed-form solution for transient lamb wave propagation behavior generated by a surface-bounded rectangular lead zirconate titanate (PZT) with d31 mode, which is assumed to be plane stress due to its thin thickness, on an elastic isotropic plate using reciprocity theorem, which uses a virtual wave to obtain the explicit solution for real state, and the normal mode expansion. The electromechanical coupling between PZT actuator and the plate is solved by modeling the shear stress continuous distribution acting on the surface of the plate. The Fourier transform of force thus can be attained by multiplying the stress with area. Having the displacement continuity between actuator and plate, the transient response of plate to the force in the frequency domain can be calculated by equaling it to be a summation of symmetric and antisymmetric Lamb wave modes. For a given input voltage impulse, the transient sensor responses are evaluated by voltage output of the PZT sensor bonded on the plate surface away from the PZT actuator.

9064-51a

Electro-thermo-mechanical coupled elastodynamic model for anisotropic guided wave propagation analysis

Luke Borkowski, Aditi Chattopadhyay, Arizona State Univ. (United States)

Physics based computational models play a key role in the study of wave propagation for the purpose of structural health monitoring (SHM) and the development of improved damage detection methodologies. Due to the complex nature of guided waves, in particular Lamb waves, accurate and efficient computation tools are necessary to investigate the mechanisms responsible for dispersion, coupling, and interaction with damage. In this paper, a fully coupled electro-thermo-mechanical elastodynamic model for wave propagation in a heterogeneous, anisotropic material system is developed. The final framework provides the full 3D displacement, electrical potential, and thermal fields for arbitrary plate and transducer geometries, excitation waveform, and thermal boundary conditions. The model is validated theoretically and proven computationally efficient. Studies are performed on flat plates under variable thermal boundary conditions with surface bonded piezoelectric sensors to gain insight into the physics of experimental techniques used for SHM. Simulation of Lamb wave propagation in composite plates allows studies to be conducted on the effect thermal variations have on the wave behavior in the composite constituents. The developed model offers the potential to provide baseline data for SHM techniques as a function of specimen temperature. Since many studies, including the ones investigated in this paper, are difficult to perform experimentally, the developed model provides a valuable tool for the improvement of SHM techniques.

9064-52b

Structural system identification of buildings by a wave method based on a layered Timoshenko beam model

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The presented work is relevant for structural health monitoring (SHM) of buildings and early detection of earthquake damage (during or immediately after the event), based on recorded acceleration response by an array of sensors in the building. It presents recent developments in a wave method for SHM based on identifying the wave propagation characteristics of the structure. Previously, the wave velocities of vertically propagating waves were identified from cross-correlation of motions recorded at different levels, or by fitting shear beam models, by matching pulses in impulse response functions. The presented work involves fitting a more realistic model, such that accounts for wave dispersion due to bending deformation, which is present to some degree in real buildings, as well as for variation of the building properties with height. The model is a layered Timoshenko beam. The model impulse response functions are computed from transfer-functions derived by the propagator matrix approach. A combination of simulated annealing and the Levenberg-Marquardt algorithms is used to fit the model impulse responses, within specified time windows, and identify the model parameters. Results are shown for a densely instrumented 9-strory reinforced concrete moment frame/shear wall building. The effect of dispersion and variation of the identified parameters with height is discussed, as well as further implementation in SHM systems.

9064-53b

Wave transmission across bolted interfaces on satellites

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Analytical modeling and environmental testing are important processes in designing, assembling, and launching satellites. The assembly process can introduce uncertainty in both structural and thermal model of interfaces key to system performance. Structural health monitoring (SHM) has the potential to lower this uncertainty by monitoring changes in the satellite and providing a method to characterize the structural properties of the satellite at critical interfaces. This manuscript considers the transmission of ultrasonic waves across a simplified but representative bolted interface for a satellite. We first experimentally examine the effect of bolt torque on wave transmission. Next, we delineate the effects of bolt load versus an external preload on wave transmission. The waves are excited and received using a pitch-catch arrangement of gridded piezoelectric wafers around the bolted interface. The effect of the external load on wave transmission is considered by arranging the fixture such that 1) the external load augments the bolt load in compressing the interface, and 2) the bolts take only a small amount of the load, while the external load compresses the interface. We examine the effect of the loading on time of flight, phase and amplitude of the waves across the interface, in each series of test. We envision that these studies are the first step in using Ultrasonic waves to characterize stiffness, damping, slip resistance, and thermal conductance across interfaces. The ultimate goal of this research is to improve the accuracy of numerical models, reduce assembly costs, and reduce likelihood of failures during environmental testing.

9064-54b

Reliable predictions of micro-anomalies from macro-observables

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A stochastic multi-scale based approach is presented in this work to detect signatures of micro-anomalies from macro-level response variables. By micro-anomalies, we primarily refer to micro-cracks of size 10--100 micro-m (depending on the material), while macro-level response variables imply, e.g., strains, strain energy density of macro-level structures (typical size often varying at the order of 10--100 m). The micro-anomalies referred above are not discernible to the naked eyes. Nevertheless, they can cause catastrophic failures of structural systems due to fatigue cyclic loading that results in initiation of fatigue cracks. Analysis of such precursory state of internal damage evolution, before a macro-crack visibly appears (say, size of a few cms), is beyond the scope of the conventional crack propagation analysis, e.g., classical fracture mechanics. The present work addresses this issue in a certain sense by incorporating the effects of micro-cracks into the macro-scale constitutive material properties (e.g., constitutive elasticity tensors) within a probabilistic formalism based on random matrix theory, maximum entropy principle, and principles of minimum complementary energy and minimum potential energy. Distinct differences are observed in the macro-level response characteristics depending on presence or absence of micro-cracks. This particular feature can now be used to reliably detect micro-cracks from experimental measurements of macro-observables. The present work, therefore, further proposes an efficient and robust optimization scheme: (1) to identify locations of micro-cracks in macroscopic structural systems, say, in an aircraft wing which is of the size of 10--100 m, and (2) to determine the weakened (due to the presence of micro-cracks) macroscopic material properties which will be useful in predicting the remaining useful life of structural systems. The proposed optimization scheme achieves better convergence rate and accuracy by exploiting positive-definite structure of the macroscopic constitutive matrices.

9064-55a

Fatigue crack detection using nonlinear vibro-acoustic cross-modulations based on the Luxemburg-Gorky effect

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This paper investigates the nonlinear cross-modulation vibro-acoustic technique for fatigue crack detection in metallic structures. The method is used in an aluminium plate instrumented with low-profile piezoceramic excitations. The plate is excited simultaneously with two harmonic signals: a slowly amplitude-modulated vibration pumping wave and a constant-amplitude probing wave. The frequency of both excitation signals coincides with the resonances of the plate. The wave modulation is transferred from the pumping to the probing wave in the presence of impact damage. This Luxemburg-Gorky effect is exhibited in a power spectrum of the probing wave by a pattern of sidebands around the carrier harmonic. The results show that the amplitude of sidebands is related to the severity of damage. Various effects related to modulation intensity and energy dissipation are investigated.

9064-56a

Evaluation of frost damage in cement-based materials by a nonlinear elastic wave technique

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Frost resistance of concrete is a major concern in cold regions. Nowadays RILEM (International union of laboratories and experts in construction materials, systems and structures) recommendations provide two alternatives for evaluating frost damage by nondestructive evaluation methods in concrete like materials. The first method is based on the ultrasonic pulse velocity measurement while the second alternative technique is based on the resonant vibration test. In this study, we monitor the frost damage in Portland cement mortar samples with water to cement ratio of 0.5 and aggregate to cement ratio of 3. The samples completely saturated by water are frozen for 24 hours at -25ºC. The frost damage is monitored after 0, 5, 10, 15 and 20 freezing-thawing cycles by nonlinear impact resonance acoustic spectroscopy (NIRAS). The results obtained are compared with those obtained by resonant vibration tests, the second alternative technique recommended by RILEM. The obtained results show that NIRAS is more sensitive to early stages of damage than the standard resonant vibration tests.

9064-57a

Acoustic microscopy, electron microscopy, and hybrid microcontinuum physics for quantifying damage incubation in 5XXX aluminum

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It has been found that there is a possible interaction between intrinsic material state and ultrasonic wave signal at multiple length and time scale. But, quantifying such state, before their manifestation, has not been investigated properly. Traditional approach is to understand the failure mode of materials through best plausible mathematical model obtained from experimental observations. Such failure models could reveal damage mechanism and their possible failure modes but could not help in diagnose the material's current state (state awareness). For such information health monitoring and NDE would be the best choice. But traditional analysis of ultrasonic NDE data restricted to sub millimeter scale. There has been a continuous thrive to increase such resolution to submicron level using nonlinear ultrasonic techniques. Although physics of nonlinear wave propagation in materials successfully revealed precursor to damage state in materials, another pathway has been adopted in this paper which is also equally capable of quantifying precursor to damage state in materials. In this work we have adopted microcontinuum physics for material description and obtained nonlocal dispersion curves for the pristine materials with varying intrinsic length scale parameters. Using Acoustic Microscopy and Electron Microscopy we have investigated 5xxx Aluminum specimens at different fatigue level. Three specimens with different level of incremental fatigue cycles were investigated and their time evolution of damage entropy were calculated from the intrinsic length scale parameters. The damage entropy growth indicates that it is possible to quantify the precursor to damage state in materials using microcontinuum material description.

9064-58a

Experiments on a wind turbine blade testing an indication for damage using the causal and anti-causal Green's function reconstructed from a diffuse field

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The increasing demand for renewable and clean power generation has resulted in increasing sizes of rotor blades in wind turbine systems. The demanding and variable operational environments have introduced the need for structural health monitoring systems in the blades in order to prevent and detect unexpected downtime events in the operation of the power plant. Many non-destructive evaluation methods used for structural health monitoring need external excitation sources. However, several systems already accepted in the wind turbine industry use just passive. Here we present a new approach to health monitoring of a wind turbine blade using only passive sensors and the existing noise created on the blade during operation. This is achieved using a known method to reconstruct the causal and anticausal time-domain Green's function between any two points in an array of passive sensors placed in a diffuse field. Damage is indicated when the similarity between the causal and anticausal signals decrease due to nonlinearities introduced from structural damage. This method was studied experimentally using a CX-100 wind turbine test blade located at the UCSD's Powell Structural Laboratories where a diffuse field was approximated by exciting the skin of the blade with a random signal at several locations.

9064-59a

Local computational strategies for predicting wave propagation in nonlinear media

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Two local computational strategies for modeling elastic wave propagation, the Local Interaction Simulation Approach (LISA) and Cellular Automata for Elastodynamics (CAFE), are compared and contrasted in analyzing wave propagation in two-dimensional nonlinear media. Each strategy formulates the problem from the perspective of a cell and its local interactions with other cells, avoiding partial differential equations and leading to robust treatment of anisotropy and heterogeneity. The local approach also enables straight-forward parallelization. The two approaches differ in two major respects. The first is that CAFE employs both rectangular and triangular cells, while LISA considers only rectangular. The second is that LISA appeared much earlier than CAFE and has been developed to a much greater degree with a multitude of material models, cell-to-cell interactions, loading possibilities, and boundary treatments. A hybrid approach which combines the two is of great interest since the non-uniform mesh capability of the CAFE triangular cell can be readily coupled to LISA's rectangular grids, taking advantage of the built-in LISA features on the uniform portion of the domain. For nonlinear material domains, the formulations cannot be put into a one-to-one correspondence, and hybrid implementation may be more problematic. This paper addresses these differences by first presenting the underlying formulations, and then computing results for bulk pressure and shear waves. For pressure waves, results from both approaches are compared to an approximate, analytical solution based on a two-scale field representation. Differences in the LISA and CAFE computed solutions are discussed and recommendations are made for a follow-on hybrid implementation.

9064-60a

Nonlinear analysis of longitudinal wave-propagation in an axial rod with breathing crack

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A variety of vibration and wave-based damage detection techniques have been employed till date for ensuring the integrity, safety, and reliability of structural components. A majority of these techniques address the linear vibration/wave-propagation analysis of damaged components. Such techniques have lower sensitivity to the presence of incipient damages and they are susceptible to the anomalies induced by environmental and operational variability. This necessitates the development of more robust damage-detection techniques. In this regard, exploitation of nonlinearity arising from the intermittent opening/closing of crack faces could be a viable alternative. While vibration-based analysis of components containing breathing cracks is getting mature, very few researchers have addressed an analytical treatment of wave-propagation through breathing cracks.

To this end, the present work expounds a methodology for analyzing longitudinal wave-propagation in an axial rod containing a breathing crack. The crack is modeled in the form of a bilinear spring which accounts for the intermittent opening and closing of crack. Frequency-domain spectral element method is applied for performing the wave-propagation analysis. The iterative solution to spectral amplitudes of displacements is obtained by employing the Newton-Raphson algorithm. A numerical example is demonstrated at the end, which clearly shows the presence of higher harmonics in the response spectrum that are the characteristic of the nonlinearity emanating from the intermittent closing of crack faces.

9064-61a

Substructure isolation and damage identification for frame structure

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According to the characteristics of civil structure, a substructure isolation method for damage identification of simple nonlinear structure is proposed in this paper. The basic idea of substructure isolation method is described as: by using convolution combination of local response, the response of substructure boundary sensors are constrained to zeros and the sensors are converted to virtual supports, and the substructure is therefore separated from global structure. Inspiring by the idea of conversion from sensor to virtual supports by substructure isolation method, virtual supports are arranged in an appropriate place in simple nonlinear structure, then the nonlinear components was isolated from global structure, afterwards, a linear structure was used to damage identification. Finally, this substructure isolation method was introduced and its effectiveness was proved by a plane frame finite element model.

9064-62b

Structural health monitoring of pipelines rehabilitated with lining technology using acoustic emission

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Damage detection of pipeline systems is a tedious and time consuming job due to digging requirement, accessibility, interference with other facilities, and being extremely wide spread in metropolitans. Therefore, a real-time and automated monitoring system can pervasively reduce

labor work, time, and expenditures. This paper presents the results of an experimental study aimed at monitoring the performance of full scale pipe lining systems, subjected to static and dynamic (seismic) loading, using Acoustic Emission (AE) technique. Particularly, two damage mechanisms are investigated: 1) delamination between pipeline and liner as the early indicator of damage, and 2) onset of nonlinearity and incipient failure of the liner as critical damage state. AE source localization was used to estimate the extent of delamination and a pattern recognition technique based on a multivariate outlier analysis was exploited to automatically identify critical damage. The results of SHM system was then validated through visual inspection of damage in pipelines.

9064-63b

Crack detection and sensitivity analysis in pipes by using a reflection-based method

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The crack detection problem has been extensively investigated due to its practical importance on structure health monitoring, especially in rails and pipes. In this paper, a reflection-based crack detection method is developed to identify the location of the cracks in the pipes based on the amplitudes of the wave reflection coefficients.

In this method, a wave-based model of the reflection coefficient is developed with respect to the possible crack locations in the detection region to describe the reflection characteristics of guided waves in the pipes. Meanwhile, the reflection coefficients of the crack can be experimentally obtained by a generalized discontinuity method without the information of the crack location. The crack location involved in the wave-based model of the reflection coefficient can then be identified by using the measured reflection coefficients. The identification process is based on the principle that the error between the experimental reflection coefficients and the predicted ones reaches the minimum in the least-square sense.

In order to investigate the sensitivity of the wave modes and frequency ranges for crack detection, three typical guided waves in the pipes are carried out as the detecting waves. Based on the reflection-based guided wave method, the cracks with different size in the pipe are detected by using these three different waves in different frequency ranges.

The results show that the accuracy of the detection is sensitive to the wave modes of the detecting waves. The detecting waves are suggested to be selected based on the shapes of cracks. Furthermore, the detection sensitivity relies heavily on the frequency range of the waves.

9064-64b

Temperature and axial stress effects in electro-mechanical impedance method-based structural health monitoring systems

Xuan Zhu, Francesco Lanza Di Scalea, Univ. of California, San Diego (United States); Mahmood Fateh, Federal Railroad Administration (United States)

Structural health monitoring (SHM) attracted researchers focus in the last two decades to handle the aging infrastructure systems all over the world. As one of the potential solutions, Electro-mechanical impedance method (EMI) was introduced in early 1990s and has great number of potential applications in the SHM of civil, mechanical and aerospace industries. This paper presents the current investigation in UCSD on the feasibility of using an impedance-based Structural Health Monitoring (SHM) technique in monitoring the Continuous Welded Rail (CWR). The objective of this research is to investigate the temperature and axial loading effect on the existing and innovated theoretical models of the Electro-Mechanical Impedance (EMI) technique based on structural dynamics, integrated with the experimental studies. Feature vectors from analytical models and experimental results are compared. The final results illustrate that the proposed models would be promising to characterize the temperature and axial stress effects. To develop a robust and cost-effective Structural Health Monitoring system which is capable to track the stress state of structural components with the presence of temperature variations, this research is necessary before stepping into the prototype phase.

9064-65b

Determination of optimal sampling rate and Hankel matrix size for subspace SI in Shear building under earthquake

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This paper presents a subspace system identification for estimating the stiffness matrix and flexural rigidities of a shear building under earthquake. System matrices are estimated by LQ decomposition and singular value decomposition from an input-output Hankel matrix. The estimated system matrices are converted into a real coordinate through similarity transformation, and the stiffness matrix is estimated from the system matrices. The accuracy and the stability of an estimated stiffness matrix depend on the size of the associated Hankel matrix and sampling rate. The estimation error curve of the stiffness matrix is obtained with respect to the time window size and maximum row size at each time window with various sampling rate using a prior finite element model of a shear building. The time window size and sampling rate, which are consistent with a target accuracy level, are chosen through this curve. Using these candidate time window sizes and sampling rates, the estimation error curve of stiffness matrix is depicted with respect to the row size of the Hankel matrix at each sampling rate to determine the size of the Hankel matrix. Among these candidate sizes of the Hankel matrix, more proper one can be determined considering the computational cost of subspace identification. The stiffness matrix and flexural rigidities are estimated using the Hankel matrix with the candidate sizes. The validity of the proposed method is demonstrated through the numerical example of a five-story shear building model with and without damage.

9064-66b

Characterization of oxidative aging in asphalt concrete pavements using its complex moduli

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Asphalt concrete mixtures with different levels of oxidative aging, prepared by oven-aging the mixture at 135 oC for different amounts of time, were used to study the effects of oxidative aging upon the ultrasonic phase velocities and attenuation measurements. It was a observed that both the dilatational and shear velocities increase up to approximately 24 hours of aging after which they significantly decease with aging. Also, both the dilatational and shear attenuation decrease up to around 24 hours of aging, after which both attenuations strongly increase. These results are consistent with results obtained using the mechanical Disk-shaped Compact Tension (DC[T]) fracture tests. Based upon these velocity and attenuation measurements, the dynamic moduli were calculated. It was observed that the dynamic moduli increase from 0 hours to 24 hours and decrease from 24 to 36 hours of oven-aging. The modulus obtained using ultrasonic measurements is also compared with the modulus obtained using the AASHTO recommended mechanical testing. The differences are due to scattering effects, which are present in ultrasonic testing. It was also observed that to avoid the uncertainty

associated with assuming a suitable value for the Poisson's ratio, both the dilatational and shear velocities and corresponding attenuation measurements must be carried out. Furthermore, to eliminate the need for traditional mechanical testing during estimation of complex moduli, frequency-dependent ultrasonic measurements must also be carried out.

9064-67b

Effect of applied load on the non-destructive measurement of concrete strength

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Nondestructive measurement of the concrete strength is an important topic of research. Among different nondestructive testing (NDT) methods the ultrasonic pulse velocity (UPV) and rebound number (RN) techniques are the two most popular methods for concrete strength estimation. While measuring concrete strength by these methods almost all researchers have neglected the effect of applied stress or load on the concrete member. In this investigation attempts were made to properly incorporate the effect of the applied load on the strength prediction of plain and polymer concrete specimens from UPV and RN values. To achieve this goal, 4 groups of concrete specimens with different values of final strength were made. Materials used for making cylindrical specimens of 3 inch diameter and 6 inch height included regular portland cement, water and two types of aggregate - fine and coarse. After applying the load on the specimen in multiple steps - at 20%, 40%, 60% and 80% of its failure strength ?f_c?^'- the time of flight (TOF) and RN values were measured for every loading step. The recorded results showed that applied load on the member has significant effect on the measured UPV and RN values on regular and polymer concrete specimens. Therefore, to find the strength of the concrete from the UPV and RN values, the applied load on the sample should be considered as an important factor that cannot be neglected.

9064-68b

Crack detection of railway turnouts using PZT sensors

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Railway turnouts (railroad switches) are the weakest components of a rail track system. Cracks may occur in the railway turnouts due to cyclic loadings and impact loadings imposed by passing trains. It is of great significance to continuously monitor the health condition of the railway turnouts and promptly detect crack once it initiates. It is well-known that acoustic emission (AE) signals are generated when a crack initiates and propagates. Detecting the high-frequency AE signals by piezoelectric sensors can help identify the crack and its location. This paper reports the design and implementation of a PZT-based system for crack monitoring of railway turnouts. This online monitoring system is activated for signal collection by a trigger system when a train is arriving to pass through the instrumented railway turnout. It mainly detects the AE signals generated when a crack initiates during the train passage or when the initiated crack expands during the passage of a heavy haul wagon. This system has been installed on a railroad line for over one year and has successfully detected the damage occurring at a railroad switch during its service period. This paper also briefs a guided-wave-based system for monitoring of micro-cracks in rail tracks by integrating FBG and PZT sensors.

9064-95

Research on prognostics and health management technology of numerical control equipment

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Scheduled maintenance and corrective maintenance both construct the tradition l maintenance policy of numerical control equipment, which may bring some problems such as excessive maintenance and inadequate maintenance. Aiming at this phenomena, Prognostics and Health Management ?PHM?technology is introduced to improve the reliability and availability of numerical control equipment.Before using this technology, Failure Mode Effects and Criticality Analysis (FMECA) shoud be firstly made for all the subsystems of numerical control equipment. FMECA is indispensable before PHM, and its purpose is to identify the key subsystems which are suitable for using PHM technology, find out the failure mechanisms of this subsystems, provide references for building failure mechanism models and defining conditional parameters being monitored. Then, a PHM system of numerical control equipment is desined. In this system, every conditional parameter of key subsystems is monitored by various sensors according to its respective failure mechanisms. A method based on multi - sensor data fusion is built to process information from sensors.The method uses the neural network algorithm. Applying the method can analyze the operation condition of numerical control equipment, and then prognose its performance degradation, life evaluation, machining accuracy, and reliability. All the results can supply helpful evidence for making maintenance poligy. Finally, key issues of implementing PHM thenology in numerical control equipment are cited with the goal of better pratical uses.

9064-96

The phase transition method for SAR measurement in MRI

Fabrizio Barone, Rocco Romano, Fausto Acernese, Rosangela Canonico, Univ. degli Studi di Salerno (Italy)

During a MR 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. Strict limits to the SAR levels are imposed by patient safety international regulations and SAR measurements are required in order to verify its respect.
The recommended methods for mean SAR measurement are quite problematic and often require a maintenance man intervention and long stop machine. The phase transition method is a no-calorimetric method to measure SAR in MRI which has the advantages to be very simple and to overcome all the typical calorimetric method problems. It does not require in gantry temperature measurements, any specific heat or heat capacity knowledge, but only mass and time measurement. On the other hand, it is necessary to establish if all deposited power SAR can be considered acquired and measured. In this paper, that will be shown.

9064-97

The PRICONA algorithm for biological spectra normalization

Fabrizio Barone, Rocco Romano, Fausto Acernese, Rosangela Canonico, Univ. degli Studi di Salerno (Italy)

There is increasing use of spectroscopic techniques, such as high-

resolution NMR spectroscopy, to examine variations in cell metabolism and/or structure in response to numerous physical, chemical, and biological agents. In these types of studies, in order to obtain relative quantitative information, a comparison between signal intensities of control samples and treated or exposed ones is often conducted. The methods thus far developed for this purpose are not directly related to the overall intrinsic properties of the samples, but rather to the addition of external substances of known concentrations or to indirect measurement of internal substances. Another possibility is to estimate, by an opportune algorithm, a normalization constant which takes into consideration all cell metabolites present in the sample. Recently, a new normalization algorithm, based on Principal Component Analysis (PCA), was presented. PCA is a well-known statistical technique for analysis of large, multivariate datasets, which extracts the basic features of the data. The PRICONA (PRIncipal COmponent Normalization Algorithm) algorithm use PCA in a new totally different manner: PCA is, in fact, used to normalize spectra in order to obtain quantitative information about the treatment effects. In this paper, it is shown that PRICONA can be used in the time domain, that is on NMR FIDs (Free Induction Decay) instead of on NMR spectra. That is advantageous because NMR FIDs do not require any operator dependent manipulation. The algorithm was tested by Monte Carlo simulations of NMR FIDs.

9064-98

Damage detection and locating using tone burst and continuous excitation modulation method

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Most of the components of modern structures operate within the limit of the structural material strength. However, due to cyclic loading over their service life, invisible fatigue cracks may develop in the structures. Such invisible damage could develop quickly in an uncontrolled manner and cause catastrophic failure. Therefore, it is important to monitor structures, detect incipient damage and provide an early caution for structural condition.

Among structural health monitoring techniques, nonlinear ultrasonic spectroscopy methods are found to be effective diagnostic approach to detecting nonlinear damage such as breathing crack, due to their sensitivity to incipient structural changes. For mixed frequency response method, ultrasonic waves with two different frequencies are used as fundamental spectral components. In the response, the appearance of harmonics and sidebands can indicate the existence of nonlinear damage.

In this paper, an active elastic wave sensing and structural natural frequencies nonlinear modulation method was developed to detect a fatigue nonlinear damage on a plate. The method is different with nonlinear wave modulation method which recognizes the modulation of low-frequency vibration and high-frequency ultrasonic wave; it recognizes the modulation of high-frequency ultrasonic wave and structural natural frequencies in random vibration environment. In the experiment, active interrogating waves and an excitation of scanning frequency were imposed on an aluminum plate at the same time. The modulation of active elastic wave sensing and structural natural frequencies was observed, indicating the presence of nonlinear damage. The results of experiments show that the proposed method is capable of detecting the nonlinear damage successfully.

9064-99

Nonlinear ball chain waveguides for acoustic emission and ultrasound sensing of ablation

Stephen Pearson, Dryver R. Huston, Jason Meyers, Walten Owens, The Univ. of Vermont (United States)

Harsh environment acoustic emission and ultrasonic wave sensing applications often place the sensor in a remote more benign physical location. Waveguides transmit elastic waves between structural location under test and the transducer. Normally waveguides are designed to have high fidelity over broad frequency ranges to minimize distortion – often difficult to achieve in practice. This paper reports on an examination of using nonlinear ball chain waveguides for the transmission of acoustic emission and ultrasonic waves for the monitoring of thermal protection systems undergoing severe heat loading, leading to ablation and similar processes. Experiments test the nonlinear propagation of solitary, harmonic and mixed harmonic elastic waves through a copper tube filled with steel and elastomer balls. Mechanical pulses of varying time widths and amplitudes are launched into one end of the ball chain waveguide and observed at the other end in both time and frequency domains. Similarly, harmonic and mixed harmonic mechanical loads are applied to one end of the waveguide. The corresponding frequency responses, including intermodulation products, are compared based on amplitude and preloads. A nonlinear mechanical model describes the motion of the dimer chains, including sonic vacuum phenomena. Based on the results of these studies it is anticipated that a nonlinear waveguide will be designed, built and tested as a replacement for the high-fidelity waveguides presently being using in an Inductively Coupled Plasma Torch facility for high heat flux thermal protection system testing. The design is intended to accentuate acoustic emission signals of interest, while suppressing other elastic wave noise.

9064-100

Dual-durometer suction foot robot for concrete inspection

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This paper presents developments in using dual-durometer pneumatic suction feet for gripping onto concrete surfaces as part of a multi-legged robotic climbing system for inspecting concrete structures with vertical walls. The dual durometer technique presents a compliant suction tip to the concrete to produce a good seal against an irregular surface, and stiff component to provide the structural rigidity needed for walking. Individually actuated pneumatic Venturi vacuum generators provide the suction from positive pneumatic pressure in a six-legged robot capable of carrying sensors, such as lightweight ground penetrating radar.

9064-101

The study on the reliability of the actuator of FAST using FTA method

Ming Zhu, Qi Ming Wang, National Astronomical Observatories (China)

China is building, in Guizhou province, a Five-hundred meter Aperture Spherical radio Telescope (FAST), which is the largest single dish radio telescope in the world. As the most important mechanism, nearly 2300 actuators are there in FAST. Its reliability study is of great importance. The main purpose of this paper is to qualitatively analyze mechanical reliability of the actuator. This paper is organized in this way: first the design of the actuator with a complex hybrid mechanism is described; then the actuator is divided into two subsystems according to their functions; finally Fault Tree Analysis (FTA) is adopted to produce the failure logic diagram of each subsystem. Hierarchically, the main fault in each subsystem is treated as top event. The fault resulted from the blocks in subsystem is defined as sub events, and so on. Fault caused by basic elements of in the system is bottom events. The most critical factor that affects the reliability of actuator is found through FTA method. This study provides a theoretical analysis to the reliability, which is the basis for optimizing the design of the actuator in the next stage.

9064-69

Realising elastodynamic cloaking

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In recent years there has been considerable interest in the theory and practice of meta-materials for cloaking, originally in the context of electromagnetic waves but later in acoustics and elastodynamics. The last is more difficult because, unlike the electromagnetic and acoustic wave equations, Navier's equations are not invariant under general coordinate transformations. In theory, elastodynamic cloaking can be achieved by the now conventional method of coordinate transformations in the case of antiplane elastic waves in two dimensional cylindrical systems. But the cloak must have an anisotropic, inhomogeneous shear modulus and inhomogeneous density. Furthermore, these must assume extremal values at certain locations. Construction of such metamaterials is a non-trivial exercise which has limited progress in elastodynamic cloaking.

More recent theoretical studies show that cloaking from antiplane elastic waves can be achieved by employing nonlinear elastic pre-stress in a neo-Hookean material. This approach would appear to greatly simplify the construction of a cloaking region. Waves in the pre-stressed medium are bent around the cloaked region by the apparent shear moduli that arise from inducing inhomogeneous stress fields via an externally applied preload.

A physical experiment and the associated computational simulations are being developed to validate the applicability of this theory to practical implementations. Theoretical assumptions were relaxed: the unbounded domain being replaced by a finite cylindrical specimen; and a hyperelastic elastomer instead of a pure Neo-hookean material. A laser vibrometer is used to observe surface motions while the specimen is being sinusoidally excited. An initial proof of concept experiment has provided indications of partial cloaking behaviour and is undergoing progressive refinement in light of the encouraging test results being obtained. Transient finite-element models of this experiment predict the existence of non-perfect but significant elastodynamic cloaking effects. Experimental and computational results to date will be presented and compared.

9064-70

Micropolar elastic theory for orthotropic chiral lattice and elastic metamaterials

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Classical Cauchy elasticity is not able to characterize chirality, hence higher order theory, e.g. micropolar theory is expected. In this work, in order to appropriately describe planar chiral media with two orthogonal axes of rotational symmetry, a two-dimensional orthotropic micropolar model is developed based on the theory of irreducible orthogonal tensor decomposition.The obtained constitutive tensors display a hierarchy structure depending on symmetry of underlying microstructure. Eight additional material constants, in addition to five for the hemitropic case, are introduced to characterize the anisotropy. The developed continuum model is then validated by a homogenization procedure for a tetrachiral lattice. Further, a discrete model of two-dimensional chiral metamaterial is also constructed, from which the proposed theory can be naturally derived with some of the effective micropolar constants being negative. It is evidenced that the wave behavior is more precisely described by the proposed theory.

9064-71

Active acoustic metamaterials with double negative effective density and elasticity using a fractional derivative controller

Amr M. Baz, Univ. of Maryland, College Park (United States)

A class of active acoustic metamaterial (AAM) is presented. The proposed AAM consists of an acoustic transmission line connected in parallel to an array of Helmholtz resonators that are provided with actively controlled boundaries. In this manner, the AAM is in effect an assembly of periodic cells, each of which consists of a Helmholtz resonator connected in parallel to two sections of the transmission line. The two sections meet the Helmholtz resonator at its neck. The local control action at each Helmholtz resonator of a unit cell is generated by using a Fractional Derivative (FD) controller that relies in its operation on the measurement of the flow resulting from the deflection of the resonator boundary and the flow rates inside the two transmission line sections before and after the resonator. Such a single local control action is shown to be capable of controlling the local effective density and elasticity of each unit cell.

A lumped-parameter model is developed to model the dynamics and control characteristics of the AAM under different gains and exponents of the FD controller. The model is exercised to demonstrate the ability of the FD controller in generating metamaterials with double negative effective density and elasticity over broad frequency ranges as compared to conventional Proportional and Derivative (PD) controllers.

With such capabilities, the development of AAM with FD control action may provide viable means for generating desirable spatial distributions of density and elasticity over broad frequency band using a small number of control actuators.

9064-72

Wave propagation in 2D and 3D magneto-elastic meta-structures

Massimo Ruzzene, Marshall Schaeffer, Georgia Institute of Technology (United States)

The paper discusses the wave propagation characteristics of two-dimensional (2D) and three-dimensional (3D) magneto-elastic meta-structures, periodic lattices governed by a combination of elastic and magnetic forces. These structures demonstrate the ability to undergo large topological and stiffness changes, which allows for dramatic changes in wave propagation characteristics.

The analysis is conducted using a lumped mass system of magnetic particles with both translational and rotational degrees of freedom. Particles within the lattice interact through axial and torsional elastic forces as well as magnetic and damping forces. Instabilities caused by the highly nonlinear distance-dependent and orientation-dependent characteristics of magnetic interactions are exploited in combination with particle contact to bring about the desired changes in the topology and stiffness of the lattices. The result is multiple stable lattice configurations with very different properties.

The propagation of plane waves is predicted by applying Bloch theorem to lattice unit cells with linearized interactions. Results from Bloch analysis are then verified through direct numerical simulations. The propagation of plane waves in these lattices before and after topological changes is compared, and large differences are evident.

9064-73

Acoustic metamaterial structures based on multi-frequency vibration absorbers

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A new metamaterial beam based on two-mass multi-frequency vibration absorbers for broadband vibration absorption is presented. For an infinite metamaterial beam, governing equations of a unit cell are derived using the extended Hamilton principle. The existence of two stopbands is demonstrated using a model based on averaging material properties over a cell length and a model based on finite element modeling and the Bloch-Floquet theory for periodic structures. For a finite metamaterial beam, because these two idealized models cannot be used for finite beams and/or elastic waves having short wavelengths, a finite-element method is used for detailed modeling and analysis. How the spring-mass-damper subsystem creates two stopbands are explained in detail. For an incoming wave with a frequency in one of the two stopbands, the absorbers are excited to vibrate in their optical modes to create shear forces to straighten the beam and stop the wave propagation. For an incoming wave with a frequency outside of but between the two stopbands, it can be efficiently damped out by the damper with the second mass of each absorber. Hence, the two stopbands are connected into a wide stopband. Numerical examples validate the concept and show that the structure's boundary conditions do not have significant influence on the absorption of high-frequency waves. However, for absorption of low-frequency waves, the structure's boundary conditions and resonance frequencies and the location and spatial distribution of absorbers need to be considered in design, and it is better to use heavier masses for absorbers.

9064-74

Vibration characteristics of metamaterial beams with periodic local resonances

Amr M. Baz, Univ. of Maryland, College Park (United States)

The vibration characteristics of metamaterial beams manufactured of assemblies of periodic cells with built-in local resonances are presented. Each cell consists of a base structure provided with cavities filled by a viscoelastic membrane that supports a small mass to form a source of local resonance. This class of metamaterial structures exhibits unique band gap behavior extending to very low frequency ranges.

A finite element model (FEM) is developed to predict the modal, frequency response, and band gap characteristics of different configurations of the metamaterial beams. The model is exercised to demonstrate the band gap and mechanical filtering capabilities of this class of metameterial beams. The predictions of the FEM are validated experimentally when the beams are subjected to excitations ranging between 10-5000Hz. It is observed that there is excellent agreement between the theoretical predictions and the experimental results for plain beams, beams with cavities, and beams with cavities provided with local resonant sources.

The obtained results emphasize the potential of the metamaterial beams for providing significant vibration attenuation to frequencies as low as 20 Hz and exhibiting band gaps extending to 200 Hz. Such characteristics indicate that the metamaterial beams are more effective in attenuating and filtering structural vibrations than plain beams of similar size and weight.

9064-75

Flexural vibration band gap and stress concentration properties of periodic beam with functionally graded materials

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Utilizing the transfer matrix method, the flexural vibration band gap and stress concentration properties are investigated in a periodic beam made of functionally graded material (periodic-FGM beam). The properties of tunable band gap, such as bandwidth, attenuation coefficient, in the periodic-FGM beam are elucidated, for various FGMs. Then, the stress distribution and the dynamic stress concentration factor (DSCF) of the periodic-FGM beam are calculated. Results show that a considerable stress concentration is alleviated by the application of this FGM. Finally, the effects of some important parameters on DSCF are probed.

9064-76

Elastic metamaterial beam with periodic arrays of beam-like resonators: theory and experiment

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We present a design of elastic metamaterial beams using periodic arrays of beam-like structures attached to a thin homogeneous beam. Such metamaterial beams can exhibit low-frequency flexural wave band gaps due to the interaction between the flexural modes of the beam-like structures and the host beam. We present explicit formula for the calculation of complex band structures. To understand the band-gap creation mechanism and to facilitate the design of such metamaterial beams, we also provide simple spring-mass models to characterize the low-frequency dynamic behavior of the attached beam-like resonators. To validate our theoretical model and predictions, we further fabricate a specimen and conduct a measurement of the vibration transmittance across the specimen, which indicates great vibration attenuation within the predicted band-gap frequency range. The metamaterial beams proposed in this work can find applications in the control of low-frequency vibration and wave propagation in beam-type structure, and can also be extended to other engineering structures, such as trusses, plates and lattice structures.

9064-105

Grazing incidence modeling of a metamaterial-inspired dual-resonance acoustic liner

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To reduce the noise emitted by commercial aircraft turbofan engines, the inlet and aft nacelle ducts are lined with acoustic absorbing structures called acoustic liners. Traditionally, these structures consist of a perforated facesheet bonded on top of a honeycomb core. These traditional perforate over honeycomb core (POHC) liners create an absorption spectra where the maximum absorption occurs at a frequency that is dictated by the depth of the honeycomb core; which acts as a quarter-wave resonator. Recent advances in turbofan engine design have increased the need for thin acoustic liners that are effective at low frequencies. One design that has been developed uses an acoustic metamaterial architecture to improve the low frequency absorption. Specifically, the liner consists of an array of Helmholtz resonators separated by quarter-wave volumes to create a dual-resonance acoustic liner. While previous work investigated the acoustic behavior under

normal incidence, this paper outlines the modeling and predicted transmission loss of a dual-resonance acoustic metamaterial when subjected to grazing incidence sound.

9064-77

Damage location by ultrasonic Lamb waves and piezoelectric rosettes

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An approach based on Macro-Fiber Composite (MFC) transducer rosettes and ultrasonic guided waves is proposed for damage location in plate-like structures. By using the directivity behavior of the three MFC sensors in each rosette, the direction of an incoming wave generated by scattering from damage can be estimated without knowledge of the wave velocity in the structure. Two rosettes suffice to pin-point the location of a scatterer in a planar structure. The technique does not have the drawbacks of time-of-flight triangulation, requiring information on wave velocity, present when testing anisotropic materials, tapered sections, or any structure under temperature fluctuations. The effectiveness of the piezoelectric rosette method is tested experimentally on an aluminium plate with a simulated damage subjected to a large temperature variation. Comparisons are made with the conventional time-of-flight-based method. The experiments confirm the increased robustness of the rosette method compared to the time-of-flight method under temperature variations.

9064-78

Guided wave interaction with defects in isotropic and composite plates

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Development of structural health monitoring (SHM) tools for composites continues to be a major research focus in the aerospace community as advanced materials are used in new systems. Guided wave (GW) SHM is one of the most promising strategies, and recent research has greatly improved the understanding of GW propagation in pristine composite structures. In order to fully realize the benefits of GW SHM, more understanding of GW interaction with typical composite damage features is necessary.

Numerical methods offer immense capability to properly model GW and their interactions with structural boundaries and damage features. Several different numerical methods have been considered in previous works, including finite element, boundary element, spectral element, and finite difference methods. Recently, the local interaction simulation approach (LISA) has received increased attention due to its computationally efficient and reliable simulation of GW. LISA uses iterative equations (IEs) to describe the displacements at a given point based on the displacements of neighboring points at previous time steps.

The proposed paper will consider the effects of various damage features on GW propagation in isotropic and composite plates using both LISA and experimental methods. First, through-thickness holes in isotropic plates will be considered to establish LISA's ability to capture GW scattering effects of various hole sizes and positions. GW generation from piezo-ceramic wafers and piezo-composite actuators such as CLoVER will be considered. Next, through-thickness holes in composite plates will be analyzed using similar methods. Results will be compared and contrasted with those from the isotropic case to highlight the effect of increased material complexity. Finally, impact damage in composite plates will be simulated and experimentally characterized. Barely visible impact damage from a drop-weight fixture will be analyzed using laser vibrometry and PZT sensors to quantify its effect on GW fields. Both in-plane and out-of-plane displacement results will be used to characterize the effects of damage position and damage severity. The ability of LISA to accurately represent impact damage effects on GW will be considered, and different techniques to model impact damage will be evaluated.

9064-79

Lamb wave-based damage detection using matching pursuit and support vector machine classifier

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In this paper, the suitability of using Matching Pursuit(MP) and Support Vector Machine (SVM) for damage detection from Lamb wave response of thin aluminium plate is explored. The study is based on finite element simulations as well as experimentally recorded Lamb wave response of thin aluminium plates with and without damage, using piezoelectric (PZT) patches as transducers. Simulations and experiments are carried out at different frequencies for various kinds of damage. The procedure is divided into two parts - signal processing and machine learning. Firstly, MP is used for de-noising and to maintain the sparsity of the dataset. In current literature, MP is used to decompose any signal into a linear combination of waveforms that are selected from a redundant dictionary. However, the dictionary used mostly has only one type of function (Gabor, Chirplet etc). In this study MP is extended by using a combination of time-frequency functions as the dictionary. Selection of a particular type of atoms lead to extraction of important features while maintaining the sparsity of the waveform. The resultant waveform is then passed as input data for SVM classifier. SVM is used to detect the location of the potential damage from the reduced data. The study demonstrates that SVM is a robust classifier in presence of noise and more efficient as compared to Artificial Neural Network (ANN). Out-of-sample data is used for the validation of the trained and tested classifier. Trained classifiers are found successful in detection of the damage with more than 95% detection rate.

9064-80

Ultrasonic monitoring suitable for the detection of loose joints and cracks in aircraft structures

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Developed methods all based on monitoring of the transport properties of ultrasonic waves are presented and discussed concerning their suitability for monitoring of aging aircraft structures. The discussed methods covered reach from single bolt monitoring to integral monitoring of extended aircraft structures covering also parts with high loads. Examples are presented together with different monitoring schemes including different transducer systems. The applicability is critically evaluated and results are demonstrated. The presentation includes also an experimental demonstration to illustrate and exemplify the pursued task.

9064-81

Guided ultrasonic waves for the monitoring of hidden fatigue crack growth in multi-layer aerospace structures

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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. The potential of guided ultrasonic waves, propagating along large plate-like structures, for the Structural Health Monitoring (SHM) of aerospace structures has been identified. However, the sensitivity for the detection of small, potentially hidden, defects has to be ascertained. This contribution presents a study of the application of guided ultrasonic waves in multi-layered tensile specimens for the monitoring of fatigue crack growth at fastener holes in the 2nd (bottom) layer of such structures. Fatigue crack growth was monitored optically and the changes in the ultrasonic signal caused by the crack development were quantified. It was shown that hidden fatigue crack detection and monitoring using the low frequency guided 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 3D Finite-Element (FE) 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.

9064-82

Approaches to hybrid SHM and NDE of composite aerospace structures

Jennifer E. Michaels, Thomas E. Michaels, Massimo Ruzzene, Georgia Institute of Technology (United States)

Periodic inspection of aerospace structures, while essential for ensuring their safety, incurs significant costs over the structure's life and also can result in significant loss of service. Structural health monitoring (SHM), or in situ nondestructive evaluation (NDE), offers the promise of more frequent assessments of structural integrity with little or no loss of service, but such systems are not in common use. Here we consider a combined SHM + NDE approach to inspection of composite, plate-like components where the SHM system detects sites of possible damage and the follow-up NDE method utilizes the in situ SHM sensors to facilitate the inspection. To be effective for aerospace structures, this combined approach should provide comparable performance to existing NDE methods but reduce the overall inspection burden.

The specific SHM approach considered is that of a sparse guided wave array using simple transducers that are spatially distributed on the structure. Ideally such an array would provide reliable detection and localization of damage and possibly an initial size estimate with a very low false alarm rate. The NDE approach is non-contact guided wavefield imaging whereby one or more of the SHM transducers is used as a source and full wavefield data are recorded over the area of interest. This method has the advantage over conventional ultrasonic methods of being non-contact and requiring minimal surface preparation. The challenge is to obtain accurate sizing information from the wavefield, which is typically lower frequency than a conventional pulse-echo inspection.

Sparse array and wavefield data from composite specimens are presented here to illustrate the concept, including potential methodologies for detection, localization and sizing of impact damage. Preliminary calculations are shown regarding inspection time requirements as compared to standard practices based upon current hybrid system capabilities and anticipated future improvements. Conclusions are drawn regarding the practicality of such a hybrid approach including its advantages and disadvantages.

9064-83

Monitoring bolt torque levels through signal processing of full-field ultrasonic data

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Using full-field ultrasonic guided wave data can provide a wealth of information on the state of a structure through a detailed characterization of its wave propagation properties. However, the need for appropriate feature selection and quantified metrics for making rigorous assessments of the structural state is in no way lessened by the density of information. In this study, a simple steel bolted connection with two bolts is monitored for bolt loosening. The full-field data were acquired using a scanning-laser-generated ultrasound system with a single surface-mounted sensor. Such laser systems have many advantages that make them attractive for nondestructive evaluation, including their high-speed, high spatial resolution, and the ability to scan large areas of in-service structures. In order to characterize the relationship between bolt torque and the resulting wavefield in this specimen, the bolt torque in each of the bolts is independently varied from fully tightened to fully loosened in several steps. First, qualitative observations about the changes in the wavefield are presented. Next, approaches to quantifying the wave transmission and reflection from the bolted joint are discussed. Finally, a method of monitoring the bolt torque using the ultrasonic data is demonstrated.

9064-84

A data fusion approach to detect the onset of damage in aerospace components

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Developing reliable structural health monitoring (SHM) systems for aerospace applications has found great demand with the increasing use of complex materials. In particular, it is desirable to track and detect the onset of damage for efficient maintenance procedures and optimal usage of the aircraft. Consequently, a data fusion approach combining the principles of Acoustic Emission (AE) in conjunction with Digital Image Correlation (DIC) and Guided Ultrasonic Waves (GUW) are utilized in parallel to track the onset of damage in aerospace materials. To this aim, compact tension specimens made of aluminum alloys under both monotonic and cyclic loading conditions were tested and heterogeneous features sensitive to damage were correlated . The combination of DIC with the acoustic non-destructive testing (NDT) techniques provides a visual cross-validation approach to identify the changes in the acoustic features related to the initiation of damage in both time and length scales. Furthermore, microscopic observation coupled with finite element modeling is utilized to validate the primary acoustic emission sources. Finally, pattern recognition approach is then utilized to identify these features and reliably separate the sources for enhanced damage detection for real time health monitoring application.

9064-85

2D aperture synthesis for Lamb wave imaging using co-arrays

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Beam-steering capability of 2D ultrasonic arrays in Lamb wave based SHM systems allow for equivocal damage imaging and in some cases can provide mode-selection. Generally, these arrays can operate in SHM applications in the phased array (PA) or synthetic focusing (SF) mode. In the PA approach, electronically delayed signals excite transmitting elements to form the desired wave-front, whereas the receiving elements are used to sense the scattered waves. Due to that the PA mode requires rather advanced hardware and excitations at numerous azimuths to scan region of interest. To the contrary, the SF mode, assumes a single element excitation of subsequent transmitters and off-line processing the acquired data. In the simplest implementation of the technique, a

single multiplexed input and output channels are required, which results insignificant hardware simplification.

The performance of 2D imaging arrays depends on many parameters, such as, shape of the array, number of transducers and their spacing in terms of wavelength as well as the type of weighting function (apodization). Moreover, it is possible to use sparse arrays, which means that not all elements are used for transmitting and/or receiving.

In this paper the co-array concept is applied to facilitate the synthesis process of an array's aperture used in the multistatic synthetic focusing approach in Lamb waves-based imaging systems. In the coherent imaging, performed in the transmit/receive mode, the sum co-array is a morphological convolution of the transmit/receive sub-arrays. It can be calculated as the set of sums of the individual sub-arrays' elements locations.

The co-array framework will be presented here using a few different arrays topologies; starting from 1D uniform linear arrays a number of 2D configurations will be considered, e.g. cross and star-shaped arrays. The approach will be discussed in terms of point spread-functions and beam patterns of the resulting imaging systems. Both, theoretical and experimental results will be given

9064-86

Estimation of fatigue damage parameters using guided wave technique

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In the present work we have considered the problem of monitoring of crack growth in a thin plate specimen subjected to fatigue load. The structure with a cyclic plastic zone around a crack resulting from fatigue load is modeled as three regions, where the damaged region is modeled as a visco-elastic-plastic zone. Using one-dimensional analytical model, the reflected and transmitted energies of the guided waves from a fatigue crack and plastic zone is studied at a given instant of the fatigue loading. Experimental study of the reflected and transmitted energy in a dynamically loaded specimen with a crack is performed using guided waves generated by piezoelectric wafers. The reflected and transmitted energies of the guided waves are monitored at various cycles of fatigue loading till the failure of the structure. The analytical approach is validated by comparing the results obtained from the experiments. From the variation of crack length with the number of load cycles, results showing a sigmoidal behavior of fatigue crack growth rate versus change in stress intensity factor is obtained. The fatigue crack growth rate is correlated with the change in reflected and transmitted energies of the guided waves. The difference in the reflected and transmitted energy is related to the size of crack tip plastic zone from which the magnitude of loading can also be estimated. Using the determined crack size and the nature of loading the residual life can be predicted from fracture mechanics approach.

9064-31

Coupled vibroacoustic modeling of membrane-type acoustic metamaterials

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Membrane-type Acoustic Metamaterials (AMs) have demonstrated unusual acoustic applications in low-frequency sound attenuation. In this paper, an analytical model is developed to capture the coupled vibroacoustic behavior of the AM. The structure of the AM can be composed of a prestretched membrane with attached masses. To accurately capture mass finite-dimension effects on the membrane deformation, the point matching approach is adopted in which the interaction between rigid masses and the deformable membrane is properly replaced by a set of distributed point forces on their boundaries. The accuracy of the model is verified by comparisons of predictions with those by the finite element method. In particular, microstructure effects such as weight, size and eccentricity of the mass, pretension and thickness of the membrane on the resulting transmission peak and dip frequencies of the AM are investigated. New peak and dip frequencies have been found for the AM with one and two eccentric masses.

9064-87

Rotational modes in photonic crystals

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Rotational motion has been widely observed in solid composites. In this work, we developed a lumped model based on mass-spring systems to study the rotational motion in two-dimensional elastic phononic crystals comprised of square arrays of solid cylindrical scatterers in solid hosts. In the lumped model, the host medium is assumed as a point mass while the scatterer is regarded as a mass with finite size and is rotatable. The restoring force between the scatterer and the matrix is modeled by a massless spring. By using Newton's second law and Bloch theorem, we can obtain the dispersion relations from the model for transverse and rotational modes. The model gives simple analytical expressions for the frequencies of the eigenmodes at high symmetry points in the Brillouin zone, and reveals the typical features of those eigenmodes, such as the acoustic and optical modes of a di-atomic chain, rotational mode, and hybrid modes. By fitting one parameter of the spring constant from a state obtained by numerically simulation, we can reproduce the band structure by using the lumped model. The lumped model is also able to predict the occurrence of accidental degeneracy by adjusting the radius of the scatterer such that the rotation mode degenerates with a doubly degenerated dipolar mode. This accidental degeneracy leads to interesting characteristics of the band structure, where the dispersion relation becomes linear and isotropic near the degenerated point. We called such dispersion relation a Dirac-like cone in the Brillouin zone center.

9064-88

Dirac and Dirac-like cones for classical waves in periodic systems

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By using the k.p method, we propose a first-principles theory to study the linear dispersions in phononic and photonic crystals. The k.p method is a perturbation method which takes the set of eigenfunctions at a particular symmetry point of interest as the unperturbed basis to study the eigenstates in the vicinity of that point. These eigenfunctions take account of all multiple scatterings in the periodic system and can be exactly determined. Based on such a method, we develop a selection rule for the crossing point of linear dispersions, which states that a non-zero, mode-coupling integral between the degenerate Bloch states guarantees a Dirac/Dirac-like point, regardless of the type of the degeneracy. In fact, the selection rule can also be determined from the symmetry of the Bloch states even without computing the integral. Thus, the existence of Dirac/Dirac-like points can be quickly and conclusively predicted for various photonic/phononic crystals. The theory also reveals that those linear dispersions created by doubly degenerate states at the Brillouin Zone boundary can be described by a reduced Hamiltonian that can be mapped into the Dirac Hamiltonian and possess a Berry phase of ?π. On the contrary, linear dispersions created by triply degenerate states at the Brillouin Zone center cannot be mapped into the Dirac Hamiltonian and carry no Berry phase, and, therefore should be called Dirac-like

cones. Our theory is capable of predicting accurately the linear slopes of Dirac/Dirac-like cones at various symmetry points in the Brillouin zone, independent of frequency, lattice structure, and composition.

9064-89

Monitoring of corrosion damage using high-frequency guided ultrasonic waves

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Due to adverse environmental conditions corrosion can develop during the life cycle of industrial structures, e.g., offshore oil platforms, ships, and desalination plants. Both pitting corrosion and generalized corrosion leading to wall thickness loss can cause the degradation of the integrity and load bearing capacity of the structure. Structural health monitoring of corrosion damage in difficult to access areas can be achieved using high frequency guided waves propagating along the structure from accessible areas. Using standard ultrasonic transducers with single sided access to the structure, high frequency guided wave modes were generated that penetrate through the complete thickness of the structure. Wall thickness reduction was induced using accelerated corrosion in a salt water bath. The corrosion damage was monitored based on the effect on the wave propagation and interference of the different modes. The change in the wave interference was quantified based on an analysis in the frequency domain (Fourier transform) and was found to match well with theoretical predictions for the wall thickness loss. The scattering of the guided wave modes at simulated (milled) pitting corrosion defects was investigated experimentally using laser interferometer measurements. The sensitivity for the detection of hidden pitting corrosion with single sided access was verified. High frequency guided waves have the potential for corrosion damage monitoring at critical and difficult to access locations from a stand-off distance.

9064-90

Power law behavior in acoustic emissions of composites aged under cyclic loading: implications for health monitoring of the composite structures

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Fatigue degradation of fiber reinforced composites is a multi-step process involving several damage mechanisms such as matrix cracking, debonding, delamination and fiber breakage. In this research, the acoustic emissions (AE) emanating from glass/epoxy specimens subjected to fully-reversed bending fatigue tests at different frequencies and displacement amplitudes are studied. Examination of the probability density function (PDF) of the AE signatures, i.e. energy (counts), reveals two scaling zones wherein the transition from the low energy (count) to high energy (count) regime is identified. The low-energy phase represents low damage or damage-free state of the laminate characterized by a power law with an exponent of ?_E = 1.8 ± 0.05. To compute the exponent, Maximum Likelihood Estimation (MLE) is employed. It is observed that AE energy release and counts follow the statistics and power laws that do not depend on the operational conditions and specimens.

The AE measurements are affected by location of the sensors, measurement system parameters, specimen size, environmental parameters, and material properties. Therefore, defining a critical value for the AE features that holds for a variety of system variables and material properties is not plausible. However, our results shows that there exists a universal feature in the statistics of the AE signatures that can be utilized in structural health monitoring schemes to improve the generalization properties.

9064-91

A vision-based technique for damage assessment of reinforced concrete structures

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The most common damage assessment technique for concrete structures is currently visual inspection (VI). Condition assessed by VI is subjective in nature, meaning it depends on the experience, knowledge, expertise, measurement accuracy, and judgment of the inspector carrying out the assessment. In many post-event assessments, cracks data including width and pattern comprise the most indicative information about the health or damage state of the structure. However, residual closed cracks are sometimes the only available data for VI due to adjacent elastic members, earthquake displacement spectrum, or re-centering systems. Therefore, the measurements may lead to erroneous decisions. To overcome this problem, this paper proposes a novel damage index based upon Fractal Dimension (FD) analysis of residual cracks as a complementary method for VI. FD can temporally quantify crack patterns and enhance the routine inspection procedure by establishing a crack pattern recognition system. This algorithm was validated through experimental studies on two large scale reinforced concrete shear walls (RCSW). The results demonstrate the novel technique as a quite accurate estimator for damage grades and stiffness loss of the specimens.

9064-92

Using the ultrasonic LCR waves to measure welding residual stresses in stainless steel pressure vessel

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This paper investigates using ultrasonic method for stress measurement in a stainless steel pressure vessel. The ultrasonic method employs longitudinal critically refracted (LCR) waves for stress measurement. The acoustoelasticconstant, which is needed in the ultrasonic stress measurement, is measured through a hydro test. The welding residual stresses are evaluated in the axial and circumferential directions. Whole the stress measurement process is fulfilled nondestructively. It has been shown that the ultrasonic method has a good potential to be used as a nondestructive stress measurement method in the stainless steel pressure vessels.

9064-93

Simultaneous identification of loads and structural damages using state observer

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In structural health monitoring, accurate information of structural loads and damages are important on maintaining structural integrity, as well as the evidence for forensic engineering. Although both factors usually coexist in practice, there is not much investigation on their simultaneous identification. The main difficulty seems to lie in a very different type of the involved unknowns: excitations vs. structural damages.

This paper proposes a method of the simultaneous loads and structural damages identification using structural states based on Virtual Distortion Method (VDM). VDM is a fast structural reanalysis method in which virtual

distortions regard to damaged elements are introduced to simulate structural modifications or damages. Structural damages extents are taken as the optimization variables and the corresponding loads are estimated via the measured outputs and the constructed system matrices of the modified structures. Unknowns are identified by minimizing the least square distance of the measured outputs and the estimated outputs to given modifying factors. During the optimization, the system matrices of the modified structure are constructed quickly via VDM, and thus the computational efficiency is increased. A numerical frame model is used to verify the proposed method.

9064-94

The investigation for fiber Bragg grating strain sensor used in the cable tension monitoring of FAST

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The Five-hundred-meter Aperture Spherical radio Telescope (FAST) constructed in China will be the largest single dish radio telescope in the world. The cable-net in FAST is a key structure for changing the shape of the main reflector through the elastic deflection of cables. The safety and the reliability of the cable-net are the most important things in the FAST. Cable-net monitoring therefore is the focus in the health monitor system. This paper introduces a new method for cable monitoring.
The cable tension is proportional to the strain of the cable anchorage as long as the cables are in elastic range. By reading the wavelength shown on the sensor, one can know the force through the calibration curve at the site by using the relation between cable tension and sensor wavelength, which can be plotted after doing the tension test on the cable, as long as the cable is manufactured. In such a case, Fiber Bragg Grating strain sensor is placed on the cable anchorage. This paper is organized in the order of follow: frequently used cable measurement methods are compared upon the application and the limitation aspects first; then the principle of the Fiber Bragg Grating strain sensor system is introduced; the idea of applying the new cable monitoring method to the FAST project is proposed in this article; eventually an experiment will be performed to an 11-meter cable in Miyun station to verify this new method. The possibility of applying the cable tension monitoring system to FAST is concluded by then.